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THESIS

Investigation of Cross Flow Fan Propulsion for Lightweight VTOL Aircraft

by

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December 2000

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13. ABSTRACT *(maximum 200 words)*

As world population increases, road and airport congestion will become increasingly prevalent. A small, cheap VTOL aircraft which can be flown from a driveway to the workplace parking lot would reduce traffic congestion and travel time. A lightweight, single seat commuter type VTOL aircraft is envisioned as the solution to this problem. To achieve a goal of minimum weight, the aircraft aerodynamic design should be optimized for forward flight. Vertical thrust augmentation from a propulsion unit contained within the fuselage would have little detriment to forward flight aerodynamics, and the cross flow fan can be accomodated as such. Cross flow fan propulsion has not been seriously considered for aircraft use since an LTV Vought Systems Division study for the U.S. Navy in 1975. Despite an indepth knowledge of the design parameters and airflow relationships in cross flow fans, the existing data supports the hypothesis that with further development the thrust efficiency and thrust-to-weight ratio could improve to the point where this thrust producing method is viable. This study investigates the incorporation of rotary engine powered cross flow fan propulsion in a hypothetical lightweight VTOL aircraft and concludes that cross flow fan propulsion is viable but only with further investigation of power plant technology and fan design parameters and relationships.

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INVESTIGATION OF CROSS FLOW FAN PROPULSION FOR LIGHTWEIGHT VTOL AIRCRAFT

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Lieutenant Commander, United States Navy
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Submitted in partial fulfillment of the
requirements for the degree of

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from the

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ABSTRACT

As world population increases, road and airport congestion will become increasingly prevalent. A small, cheap VTOL aircraft which can be flown from a driveway to the workplace parking lot would reduce traffic congestion and travel time. A lightweight, single seat commuter type VTOL aircraft is envisioned as the solution to this problem. To achieve a goal of minimum weight, the aircraft aerodynamic design should be optimized for forward flight. Vertical thrust augmentation from a propulsion unit contained within the fuselage would have little detriment to forward flight aerodynamics, and the cross flow fan can be accomodated as such. Cross flow fan propulsion has not been seriously considered for aircraft use since an LTV Vought Systems Division study for the U.S. Navy in 1975. Despite an indepth knowledge of the design parameters and airflow relationships in cross flow fans, the existing data supports the hypothesis that with further development the thrust efficiency and thrust-to-weight ratio could improve to the point where this thrust producing method is viable. This study investigates the incorporation of rotary engine powered cross flow fan propulsion in a hypothetical lightweight VTOL aircraft and concludes that cross flow fan propulsion is viable but only with further investigation of power plant technology and fan design parameters and relationships.

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Finally, I express deep gratitude to my wife and children for their support and understanding.

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I. INTRODUCTION

As the population near major metropolitan areas continues to increase, so too will the automobile traffic congestion. Also, in areas such as San Francisco/Oakland and Silicon Valley, property values have skyrocketed to levels that the average family cannot afford which forces them into rural areas farther away from the workplace. An 80-mile drive during rush hour can take as long as three hours in these areas. Even a commute by rail or traditional aircraft still entails a delay in traffic unless the workplace is at the airport. An ideal solution for minimizing travel time in areas like this is an aircraft that can take off from a driveway at home and land in a parking lot near the workplace. Ideally the aircraft would be propelled by a combination of powerplants sized for the appropriate flight regime, either vertical or forward flight. In most vertical takeoff and landing (VTOL) aircraft, the vertical thrust requirement is very large compared to the forward flight thrust requirement. Separate powerplants for each regime would maximize fuel efficiency. A small vertical thrust augmenting device, mounted within a fuselage, could be turned off to save fuel in forward flight and would pose no drag penalty. The cross flow fan can meet this stipulation.

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II. MISSION STATEMENT

The basic design in this study is for a lightweight, single seat, vertical takeoff and landing (VTOL) commuter aircraft with detachable or foldable wings so that the aircraft can be temporarily stored in an automobile parking space. Ideally, the aircraft would also have the capability of being driven under power a short distance from the landing area to a parking space.

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III. DESIGN CONSIDERATIONS

A. AIRFRAME

A helicopter was considered, but deemed not effective for this mission due to the extreme danger posed to surrounding personnel and objects by the long rotor blades and to the large footprint required for parking/storage. Powered sailplanes can be found with detachable wings and empty weights (minus engine) of 300 pounds force (lbf). A bare-essentials composite airframe similar in construction to these sailplanes would be ideal for this mission. Also, a canard configuration would weigh less than a conventional configuration because both the wing and canard are sized to provide the lift instead of only the wing. In light of the commuter mission, the aircraft is configured for a single occupant and minimal baggage with a combined weight of 250 lbf. Fuel storage is envisioned as "wet", where the airframe structure acts as the fuel tank walls, but with a rubber-like lining.

B. THRUST PROVISION

The design focus of this thesis incorporates ducted propellers to provide both lift and cruise thrust with VTOL lift augmentation from a cross flow fan unit. To ensure adequate performance during VTOL flight, total thrust must equal at least 1.3 times the gross takeoff weight of the aircraft. Ducted propellers are more efficient in producing static thrust and provide a safety barrier for personnel on the ground. The limiting case in this design is the amount of static thrust per weight available for vertical flight. Although the aerodynamic drag from the duct will outweigh any thrust advantages at high speeds, the aircraft in this study is not designed or optimized for high-speed flight.

Cross flow fan thrust augmentation was chosen because of its relatively small size and relative ease of incorporating the unit inside a fuselage. Since engine size is driven by the vertical take off and landing requirement, turbine propulsion fuel consumption would have been inefficient during horizontal flight. Additionally, the extreme exhaust heat produced by a turbine could create unwanted damage to landing areas designed only to support automobile traffic and be a danger to bystanders.

C. POWER PLANT

Turbine engines were rejected for the reasons mentioned above. A reciprocating engine would provide the best fuel economy – an important consideration in minimizing the amount of fuel, and consequently the weight, of the aircraft. The lightest reciprocating engines, and the smallest for a given power rating, are rotary reciprocating internal combustion engines (first designed by NSU/Wankel). Engines used for this study are the aviation-compatible Rotapower® 530 series rotary engines by Freedom Motors. Although data for turbocharged Rotapower® engines was not available, this method of increasing power is well suited for the intended mission. Most, if not all, aviation turbocharged engine applications use the turbocharger to maintain a somewhat constant power rating over a large altitude range. The proposed commuter VTOL mission would not have the same power requirements as a conventional aircraft. Forward flight is envisioned at roughly 10,000 feet altitude above mean sea level at a maximum range speed for which only a small amount of thrust is needed. The maximum thrust available is required in the vertical flight regime at lower altitudes. The turbocharging scheme in this case would be similar to an automobile engine – for maximum power.

D. CURRENT AND PROPOSED DESIGNS

There are no vehicles currently available for this mission. A proposal by Moller International, called the Volanter, uses deflected thrust from four ducted counter-rotating propeller units in a four passenger VTOL. Although the Volanter has a small wing, it relies on some deflected thrust to provide lift in forward flight. In a vehicle for which minimum weight is paramount, this method of providing lift is inefficient. It will require more fuel, and consequently more thrust to perform the VTOL mission than an aircraft that relies only on conventional wings to provide lift in forward flight. A single seat design for basic transportation to and from the workplace would also weigh less and be smaller and easier to configure for temporary storage in an automobile parking space.

E. FINAL CONFIGURATION

In analyzing thrust and weight requirements, the maximum aircraft takeoff weight was revised from 1,000 lbf to 1,330 lbf. The vast majority of the airframe is graphite/epoxy with a canard and wing. Lift/cruise thrust is provided by two ducted-propeller units with vertical flight thrust augmented by a cross flow fan. The ducted propellers provide 1,042 lbf thrust and the cross flow fan provides 690 lbf thrust for vertical flight.

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IV. CROSS FLOW FAN

The cross flow fan appears to resemble a squirrel cage fan, but operates quite differently. Whereas the squirrel cage fan draws air in through the ends of its cylindrical shape and expels the air radially outward in all directions (three-dimensional flow), the airflow in a cross flow fan passes from the ducted inlet on one side of the cylindrical shaped fan and exits out the exhaust ducting on the opposite side of the fan as shown in

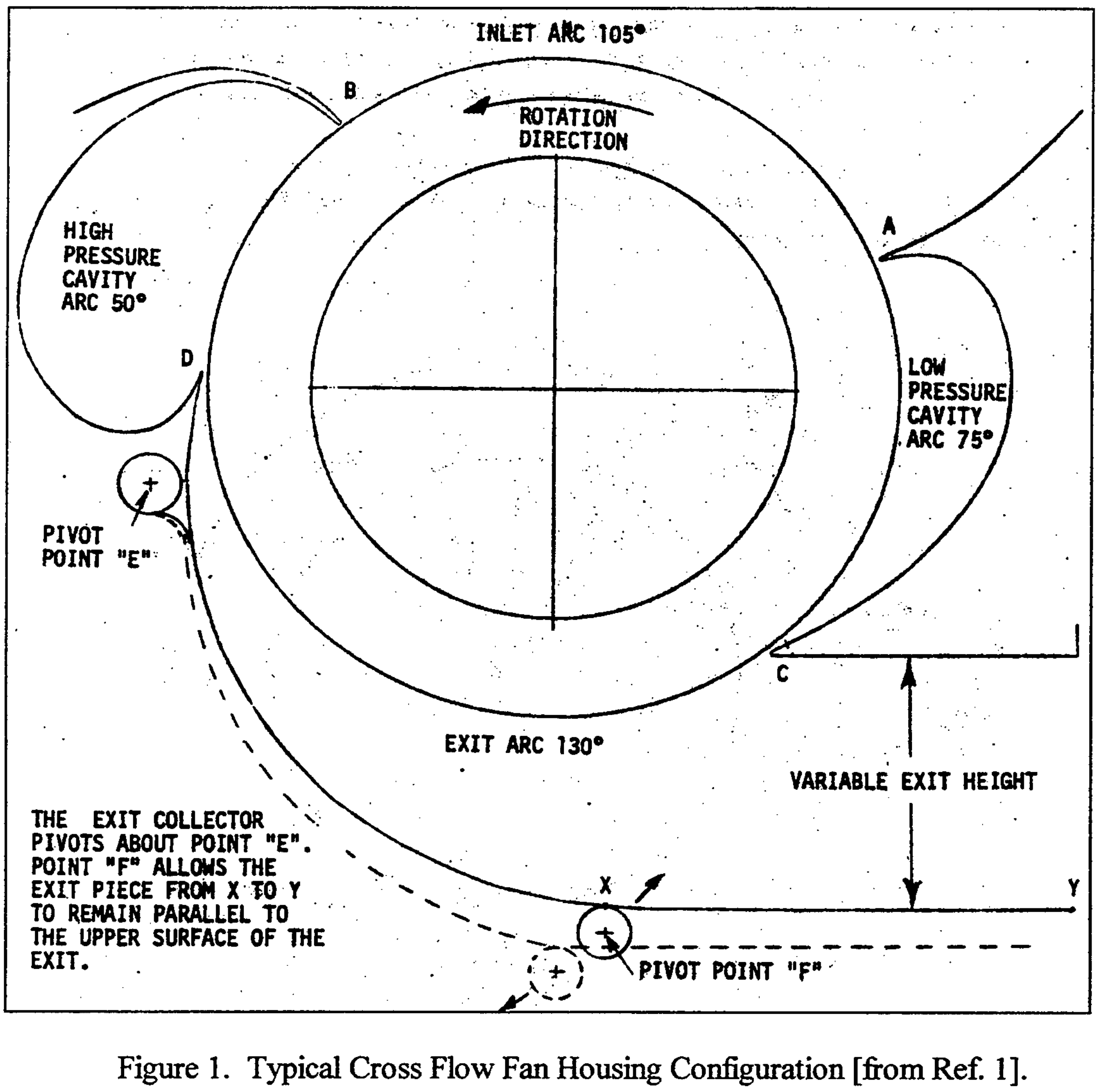

Figure 1. Typical Cross Flow Fan Housing Configuration [from Ref. 1].

Figure 1, and entails no span-wise flow. A typical cross flow fan consists of from 24 to 36 blades mounted in a driven end plate. The fan may also have a non-driven endplate opposite the driven end, a desirable addition since it eliminates efficiency loss from the blade tip clearance required without the endplate. Since the cross flow fan airflow is essentially two-dimensional, ideal airflow per unit length (blade span) can be considered constant for a given configuration: with increasing blade span, total thrust increases but

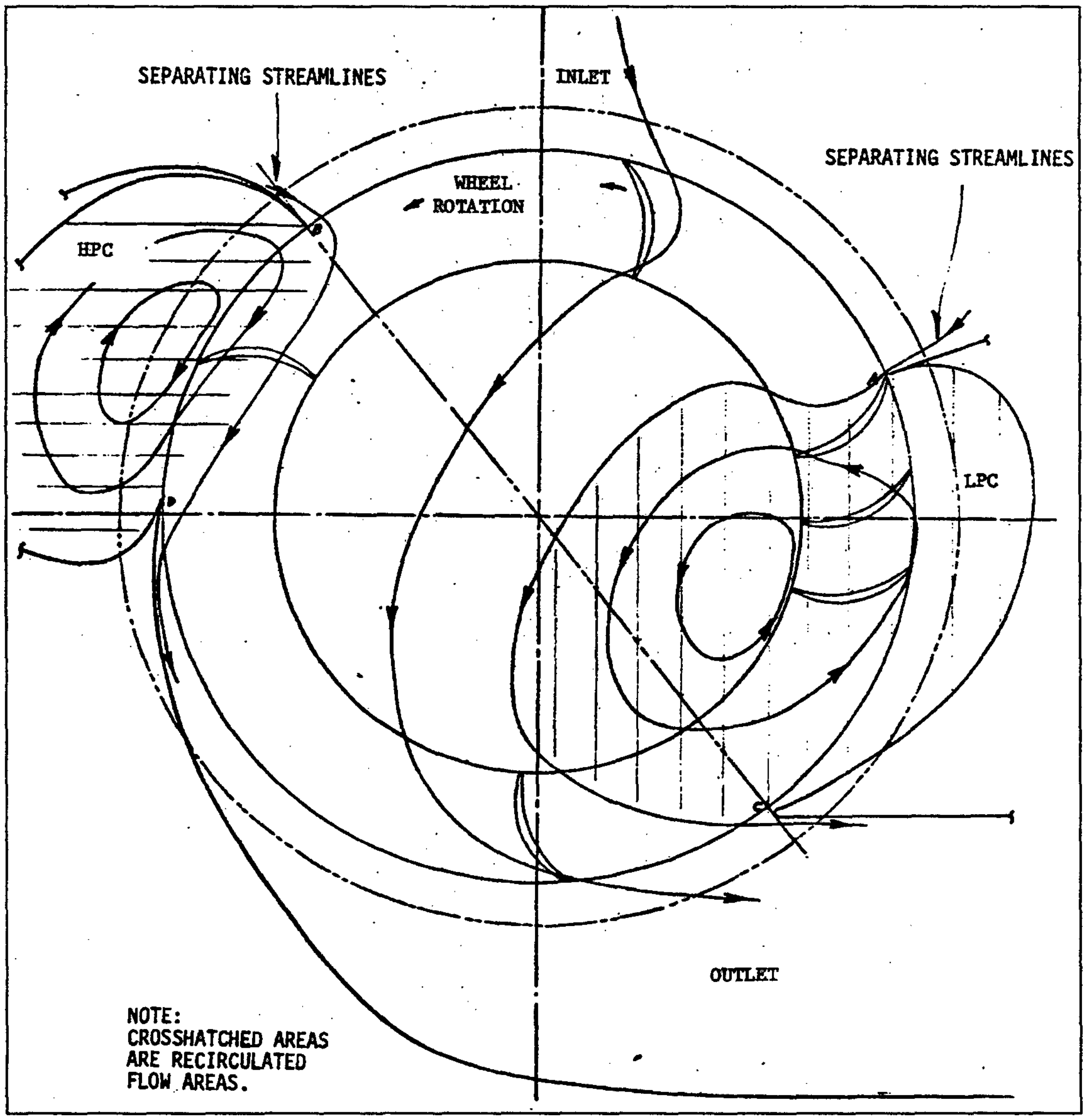

Figure 2. Typical Airflow and Vortex Locations in the Cross Flow Fan [from Ref. 1].

the mass-flow rate stays the same. Shaped cavities for high- and low-pressure air recirculation, between the inlet and exit ducting, influence airflow as shown in Figure 2 for the Vought Systems Division (VSD) (a division of the LTV Aerospace Corporation) cross flow fan design [Ref. 1]. Blade and high-pressure cavity shape differences in the VSD study were found to have only minor effects on the pressure ratio and airflow measurements, while the low-pressure cavity and exit duct shapes had significant effects on performance. The cavities are used to influence airflow recirculation between the inlet and exhaust ducts, and to maintain the position of the recirculated flow vortices. The ratio of the radial distance from the fan center of the fan blade inner edge to outer edge also greatly affected the fan performance. Despite numerous studies of cross flow fans, definitive design parameters have not been established.

A vast majority of cross flow fan data was obtained from the report of a 1975 VSD program performed under contract for the Naval Air Systems Command [Ref. 1]. In this program, VSD constructed cross flow fans measuring 12 inches in diameter and both 1.5 inches and 12 inches in span. A 12-inch span fan unit is pictured in Figure 3 [Ref. 1]. Several combinations of blade, cavity and exit duct design were evaluated. Extensive testing to optimize component shapes was not performed, but overall compression efficiencies were demonstrated to approach 70 to 80 percent. Although the cross flow fan can operate at relatively high rotational speeds – tested to 12,500 revolutions per minute (rpm) [Ref. 1] – compression efficiency reduces when sonic airflow speeds are approached in the exhaust duct. The highest efficiencies in the VSD designed cross flow fan appear to occur at rotational speeds of approximately 4,000 to

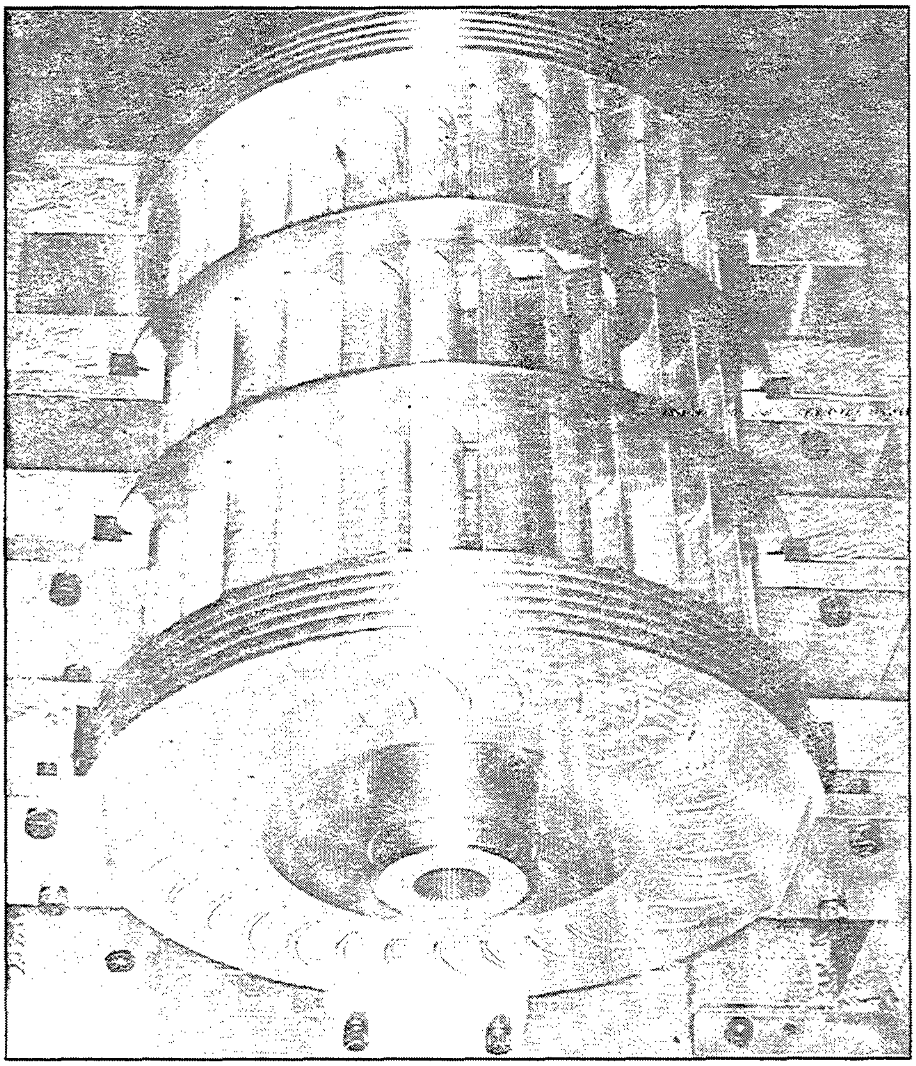

Figure 3. Typical 12 inch Span Cross Flow Fan Blades [from Ref. 1].

7,000 rpm for the configurations tested. Low speed tests (2,000 rpm or less) show a decrease in performance with decreasing fan rotation speeds [Ref. 2].

In the VSD study, cross flow fan mass-airflow rates compare favorably to axial fan flow rates. The study provides data for determining the thrust of a twelve-inch diameter cross flow fan per foot of span based on two fan blade and exit duct height configurations and with both fan designs incorporating 30 blades. Fan number 6 with an exit duct height of 4.6 inches is a more efficient use of horsepower. If driven by a 300

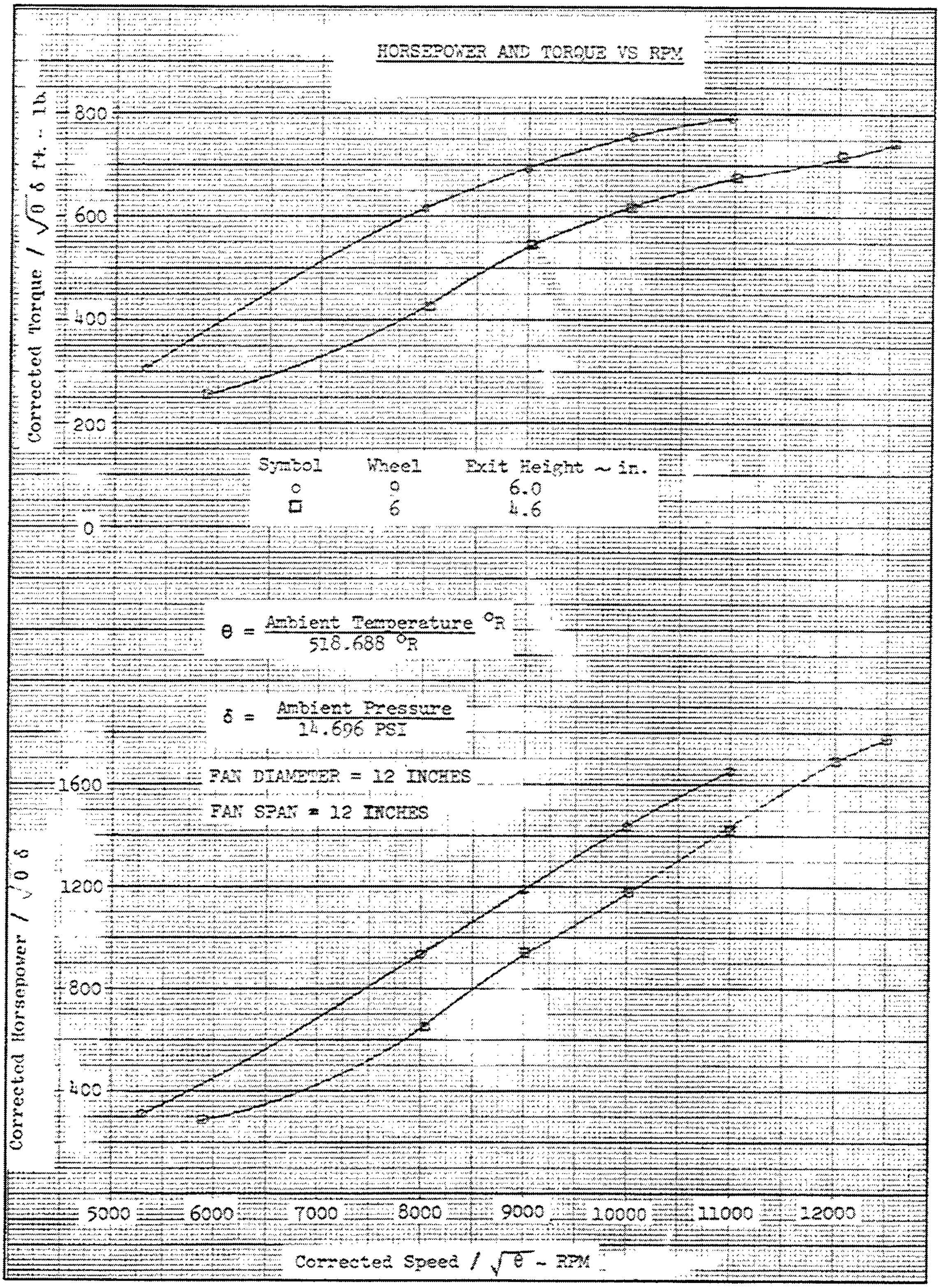

Figure 4. Horsepower and Torque vs. RPM Per Foot of Fan Blade Span [from Ref. 1].

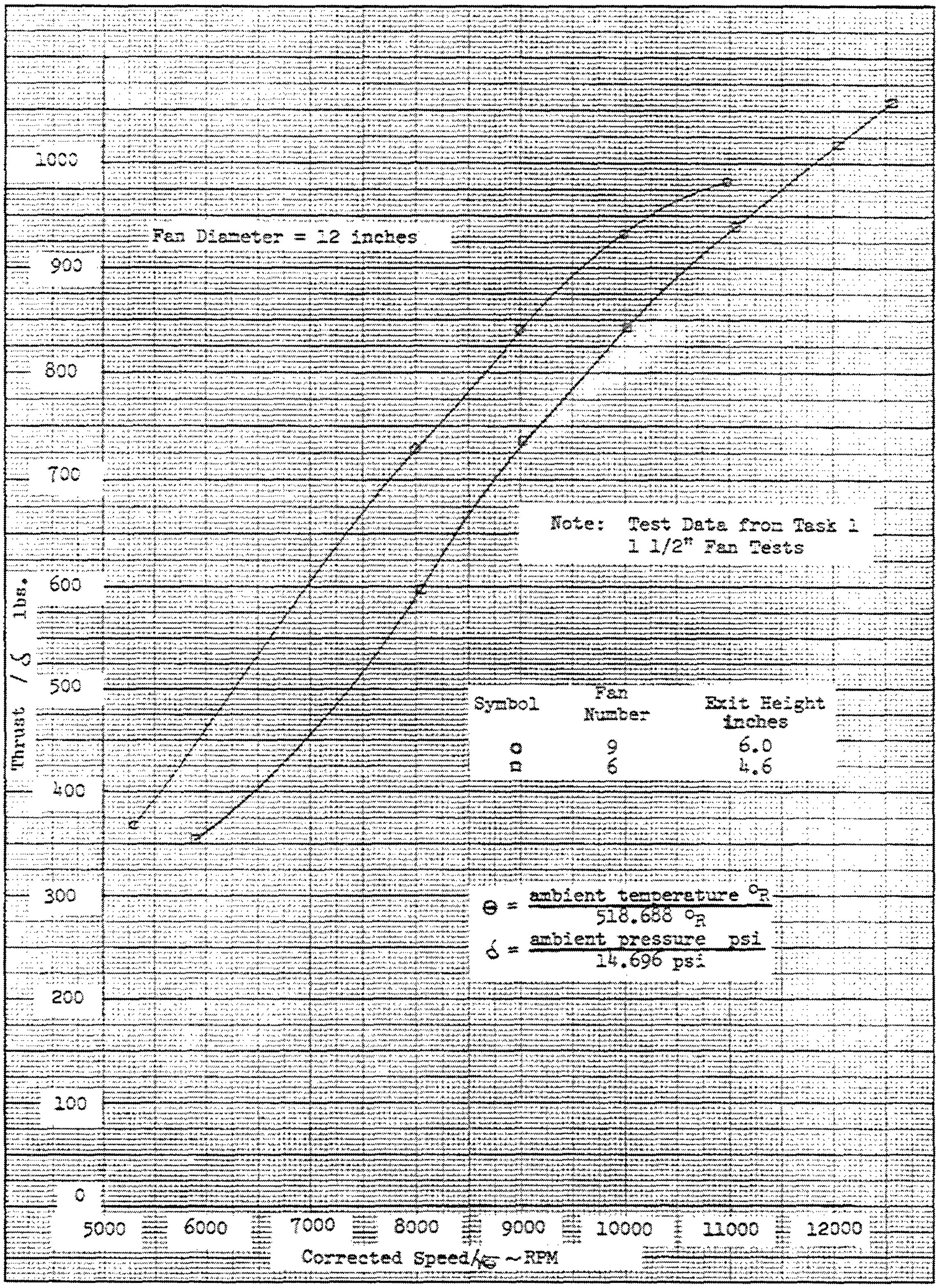

Figure 5. Thrust vs. RPM per Foot of Fan Blade Span [from Ref. 1].

horsepower engine at 6,500 rpm, it will produce approximately 345 lbf of thrust from a fan span of 10.3 inches as determined in Figures 4 and 5. The pounds force thrust per horsepower ratio for this configuration is approximately 1.15. The thrust produced by fan number 9, with a span of 6.4 inches, would only be 284 lbf if driven with the same horsepower and the same rate of rotation – a pounds force thrust per horsepower ratio of only 0.95. For this thesis, the combination of fan number 6 and the 4.6 inch exit duct height was used. Further studies of the cross flow fan would allow refinement of the blade, duct and cavity designs, and could lead to greater thrust produced per horsepower.

For the aircraft in this report, the configuration in the airframe of the cross flow fan unit is parallel to the aircraft longitudinal axis due to the total length of the unit. A total fan span of 20.6 inches is required to produce 690 lbf of thrust when driven by 600 horsepower at 6,500 rpm. The 600 horsepower requirement is met by a theoretical eight-rotor rotary engine from Freedom Motors. From this stipulation, many configurations are possible. In one configuration, a single 20.6-inch span fan would be driven by either 2 four-rotor rotary engines on either side of the fan unit or a single eight-rotor engine. The advantages of this configuration are that only two endplates are required for the single fan-unit blades, there would be less torsional bending moments on the fan blades, and less material weight would be required for the fan unit ducts. Disadvantages are the potentially greater weight of two separate engine assemblies or, for the single eight-rotor engine, the potentially heavier fan construction to withstand the torsional loads. Another configuration would use a single eight-rotor engine with a 10.3-inch span fan unit at both ends of the engine. Advantages of this configuration are a reduced weight due to use of a single engine assembly, a more rigid basic fan duct structure, and potentially a more beneficial exhaust airflow near the landing surface in the VTOL regime. The disadvantages are the weight of additional fan end-wall ducting compared to the single fan configuration and the increased torsional bending moments on the fan blades since they are driven on only one side. To accommodate the overall length of the fan-engine unit (5.55 feet), maintain an acceptable balance of weight and provide good pilot visibility, the configuration chosen was a single eight-rotor engine with a single 20.6 inch fan attached to the end of the engine. The weight differences between the configurations are most likely insignificant for the scope of this study. The finalized configuration should be based on blade/fan unit strength/weight considerations and exhaust airflow patterns. Servo actuated louvers at the cross flow fan inlet and exhaust, which open when the fan is operating, would lie flush with the aircraft skin during forward flight to minimize drag. During vertical flight the exhaust louvers, a portion of which are mounted parallel to the aircraft longitudinal axis and rest perpendicular, would be actuated as required to provide yaw control and aft thrust vectoring for transition to forward flight.

Weights of various materials for fan blade and cavity construction were closely approximated in the VSD report for a 30-inch span cross flow fan unit. Also noted were the high sound levels produced (approximately 153 dB in the exhaust plane at 6,500 rpm) and consequent opportunity for high sonic fatigue in the ducts and cavities. Heavier gauge material is required in the fan cavities and ducting to combat the sonic fatigue as well as withstand the air pressures developed within the unit. Based on scaling the VSD 30 inch span weight analysis to a 20.6-inch span fan, the expected weights of four fan compositions were derived. The blade endplates would vary in thickness somewhat, depending on span length, so the scaling is not linear – a certain minimum endplate thickness is required to resist the blade bending moment during fan rotation. Longer blade spans may also require one or more mid-span blade supports. A fan constructed with blades made of thin-wall (0.02 inch) Titanium tubing, filled with composite material for support and bonded to the end plates, should weigh approximately 30 lbf. If the blades were machined and welded Titanium, the fan would weigh approximately 40 lbf. An extruded and bonded 7075 Aluminum fan blade configuration would weigh approximately 43 lbf, and a fan built with blades of pultruded and bonded graphite-epoxy composite material could weigh as little as 25 lbf. The ultimate material choice would depend on shape consistency, strength and abrasion resistance of the fan blades. Weight scaling based on data in Reference 1 was also used to estimate the weights of the high- and low-pressure cavities and the inlet and exhaust ducting. Data from the VSD study lists the weight of a 30-inch long inlet cavity of conventional construction, which appears to be C-channels welded or riveted to plate material, as 14 lbf. An inlet duct door constructed of an aluminum alloy honeycomb sandwiched between plates, which measures 30 inches by 20 inches, is estimated to weigh 13.4 lbf in the study. Conservatively estimated from scaled VSD data, the low- and high-pressure cavities would each weigh 9.6 lbf, and the inlet and exhaust ducting 24 lbf. Therefore, a 20.6-inch span fan unit with blades made of graphite/epoxy and ducting made of aluminum and composite materials would weigh approximately 68 lbf. Combined with a Freedom Motors Rotapower® 530 eight-rotor rotary engine, which would weigh 240 lbf, the total cross flow fan system would weigh 308 lbf. With 690 lbf of thrust for this cross flow fan and engine configuration the calculated thrust-to-weight ratio is approximately 2.2.

The engine weight, scaled from data obtained from the company's web site [Ref. 3], includes starter, alternator, lubrication, fuel and ignition systems but no exhaust. For the aircraft described in this thesis, the cross flow fan is a thrust augmenter and would not require an alternator (the lift-cruise engines would provide electrical power), and the flywheel would be lightened since the fan blade end plate would provide rotational mass. The remainder of the flywheel is required to hold the ring gear that the starter motor engages. The weight of the engine cooling system is also not included in the company's estimate.

V. ROTARY ENGINE

The biggest advantages of using rotary engines in a lightweight aircraft are the power-to-weight ratio and the small size. Freedom Motors, a part of Moller International, has developed the Rotapower® 530 Series liquid cooled rotary engines [Ref. 3]. The 530 Series engines will be available in one, two, three or four rotor configurations but the modular design should allow an engine to be constructed with any number of rotors (limited by the strength of the crankshaft). Measurements of the two-rotor engine long block are 16 inches long, 11 inches high and 11 inches wide, and each additional rotor adds five inches to the length. Additionally, each configuration can be specified with one of two power ratings. The industrial rated engines have a 4,500 rpm maximum and the high performance engines a maximum of 6,500 rpm. The high performance engines operate at higher rotational speeds and as such will require more maintenance per flight hour over the life of the engine (although not specifically stated in Reference 3) due to wear of the rotor seals. Rotary engines are inherently low vibration, which allows more freedom in placement since the engine can be hard mounted or carry loads as part of the structure. The specific fuel consumption claimed for these engines is 0.4 lbf/hp-hr with a patented coating applied to the cylinder surfaces, or 0.45 lbf/hp-hr without the coating. Also claimed is a specific fuel consumption of less than 0.35 lbf/hp-hr when the engines are both stratified charged and turbo-charged. Turbo-charging would further increase the power-to-weight ratio and potentially allow smaller engines (fewer rotors) to be used for the aircraft in this thesis, but applicable information was not available. Lubrication is obtained from either burning a fuel/oil mixture or by a metered "lost oil" system [Ref. 3].

For the cross flow fan unit in this design, a high performance eight-rotor engine was used for generating 600 horsepower. Since the cross flow fan is only operational during takeoff and landing, the shorter mean time between maintenance intervals of a high performance engine would not be a limiting factor in engine choice. The ducted propellers (two in this design) are each driven by a two-rotor 150 high performance Freedom Motors rotary engine. Weight for this engine is claimed to be 90 lbf [Ref. 3], which includes starter, alternator, lubrication, fuel and ignition systems but no exhaust. To minimize weight, a heavy speed-reducing gearbox to keep the propeller tip speeds less than 0.9 Mach was not desired so the directly driven propellers are limited in maximum diameter.

VI. DUCTED PROPELLERS

Airflow in the fully established wake downstream of an unducted propeller narrows to approximately one-half of the propeller diameter, which causes the airflow to accelerate to twice the airflow speed immediately aft of the propeller. Enclosing the propeller in a duct improves its static thrust efficiency by forcing the exhaust streamlines to parallel the duct and thus preventing acceleration of the airflow. A ducted propeller that has a duct exit area equal to the propeller area will produce 1.26 times the static thrust of an unducted propeller of the same diameter [Ref. 4]. An increased diffuser ratio, the exit area divided by the propeller area, requires a longer duct to prevent flow separation from the duct wall and would increase the duct weight. The thrust efficiency advantage decreases as the axial speed of the ducted propeller is increased, as in forward flight at cruise speeds. A conservative solution for this thesis is a diffuser ratio of one, which should minimize the drag penalty during the relatively low forward flight speed (maximum range airspeed) envisioned for this design. Careful shaping of the duct should minimize the drag detriment while providing increased static thrust and decreased noise levels.

Per Reference 5, the equation

$$hp_{act} = \frac{T\sqrt{\dfrac{T}{2\rho A_R}}}{550(F.M.)}$$

was used to calculate the propeller area (A_R) required to provide the 1,042 lbf thrust not produced by the cross flow fan (690 lbf) for VTOL flight. In this equation, hp_{act} is the actual horsepower (150 per engine), T is the thrust required (607.5 lbf per propeller), ρ is the air density (0.002377 slugs/ft^3 at sea level) and F.M. is the Figure of Merit for propeller efficiency. Duct-propeller combinations tested in previous studies had an average F.M. of 0.92 [Ref. 6], therefore that value was used to calculate a propeller area of 5.16 ft^2. Assuming the diameter of the nacelle surrounding the engine centrally mounted within the duct is 13 inches, the total projected area of the inner duct is 6.09 ft^2, and the propeller diameter is 2.78 ft. The propeller tip speed was calculated using the relation

$$V_{TIP} = \frac{\pi(Dia)rpm}{60}$$

to equal approximately 947 ft/sec or 0.85 Mach at sea level with the specified propeller diameter rotating at 6,500 rpm. The maximum propeller disc loading, thrust per propeller area, is then 101 lbf/ft^2, and the maximum power loading, thrust per horsepower, is 3.47 lbf/hp.

The ducted propellers in this design are located on either side of the fuselage and mounted under the wing. Tilting ducted fan assemblies were considered, but the advantages of a cascade of variable-pitch duct exit vanes were determined to be more suitable for this design. Tilting ducts are susceptible to inlet lip stall, and consequently a loss of thrust, during transitions between vertical and horizontal flight. Exit vane cascades offer more control, and a larger margin of controllability, during transition from horizontal to vertical flight, during deceleration with steep descent angle capability, and for pitch and lateral command inputs [Ref. 7]. The cascade vanes can be further used to vary the duct exit area, a thrust optimization tool when fixed-pitch propeller blades are used.

Duct cowling constructed of composite material with a foam core would minimize both weight and propeller noise. Bladed struts placed radially around the engine nacelles would provide support for the duct. To estimate the weight of a ducted propeller in this thesis it was assumed that each duct, and associated struts and cascade exit vanes, weighs 30 lbf and each propeller weighs 20 lbf.

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VII. AIRCRAFT DESIGN

A canard configuration was chosen to minimize weight since all wings contribute to lift and are sized accordingly and due to weight and balance considerations. Advanced composite materials and technologies would be incorporated in the airframe construction to approach a sailplane-like basic weight goal of 350 lbf.

To minimize induced drag, a high-aspect ratio NASA/Langley LS(1)-0413 airfoil shape was incorporated for the wing and canard. This airfoil has both a low zero-lift drag coefficient (C_{D0}) and a low drag coefficient (C_D) at a coefficient of lift (C_L) of 0.5. The wing and canard design for this thesis incorporates an aspect ratio of 20, a taper ratio (tip chord/root chord) of 0.6 and a zero degree quarter-chord sweep. Based on the overall weight distribution, the wing must support 57.5 percent of the total weight and the canard must provide the remaining 42.5 percent of the lift during forward flight. The mean aerodynamic chords of the wing and canard are 0.8933 foot and 0.6125 foot respectively. Flaps are neither required nor desired, and roll control could come from either ailerons or spoilers. Detachable or folding wing and canard sections ease ground transportation and storage.

Control surfaces, comprised of an all-moving canard, rudder and either spoilers or ailerons, are actuated by simple cable-type controls. Total thrust control is via computer controlled throttle-by-wire fuel injection. This type of throttle control has been used for several years now in automobile engines, and it has been proven reliable. Computerized electronic throttle and cascade vane control, in combination with a gyroscopic stabilizer, is a lightweight solution to providing small, timely power adjustments to control rate of descent, pitch, yaw and roll in VTOL flight. Computerization also simplifies the pilot workload during VTOL flight because the pilot needs only manipulate a throttle to direct rate of descent, a stick to command fore-aft motion and rudder pedals to regulate yaw. Drawings of the finalized design are shown in Figures 6, 7, 8 and 9.

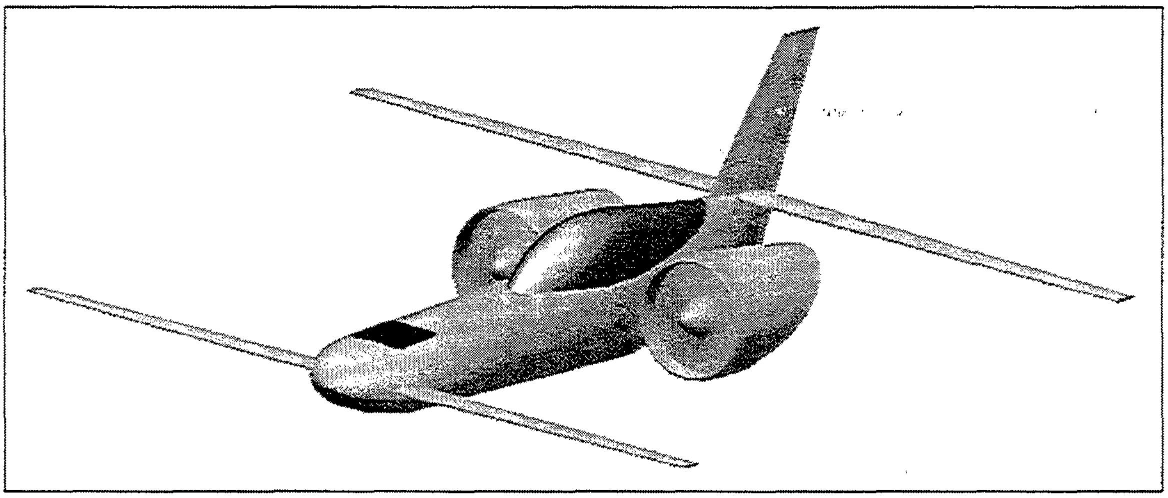

Figure 6. Front Three-quarter View of VTOL Aircraft Design.

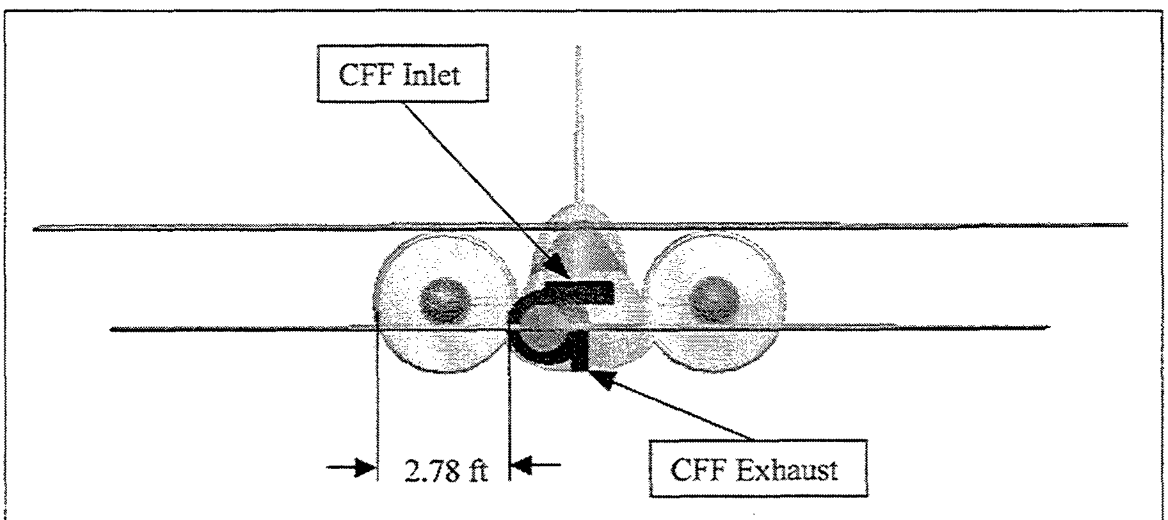

Figure 7. Front Semi-transparent View of VTOL Aircraft Design.

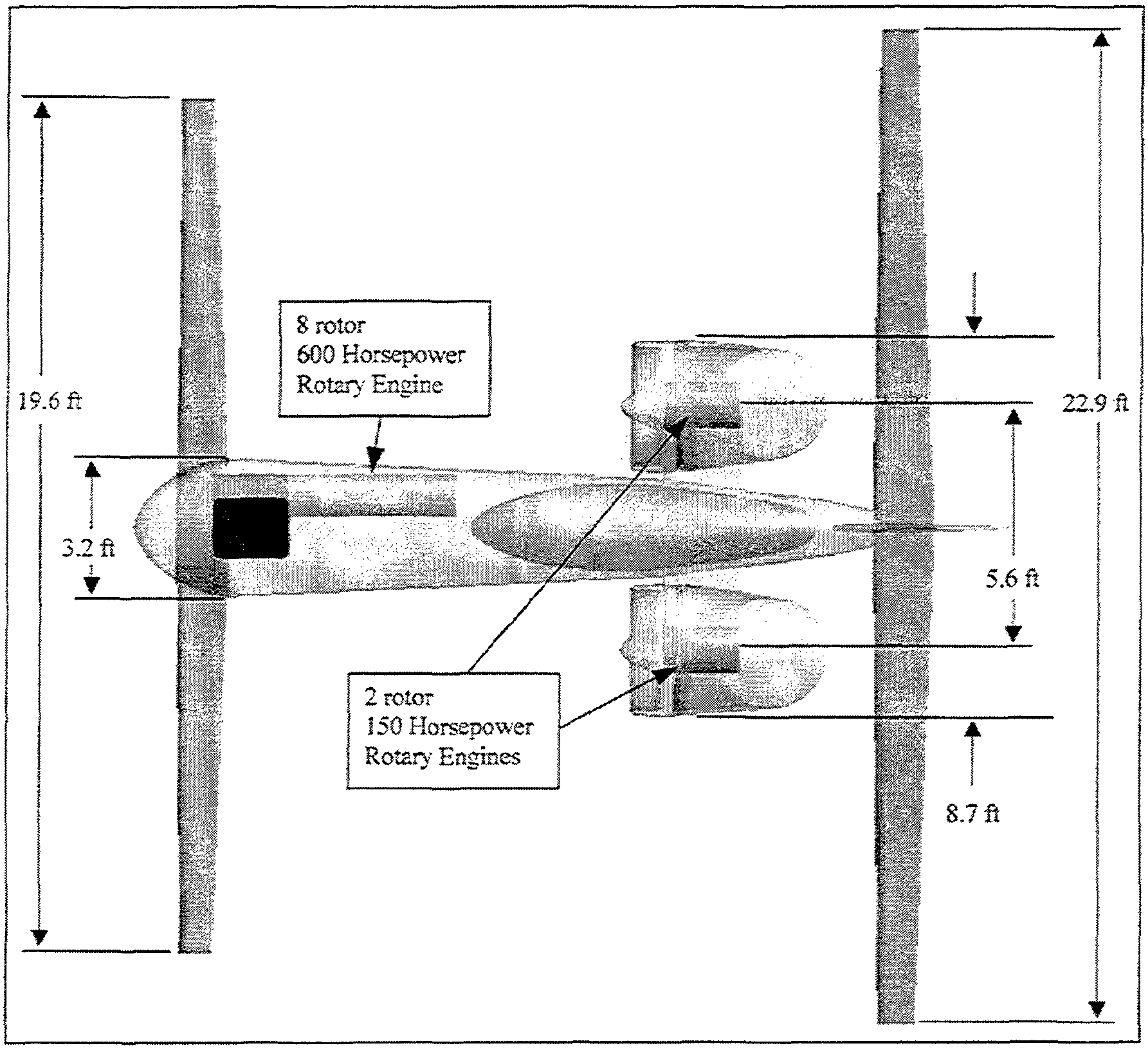

Figure 8. Top Semi-transparent View of VTOL Aircraft Design.

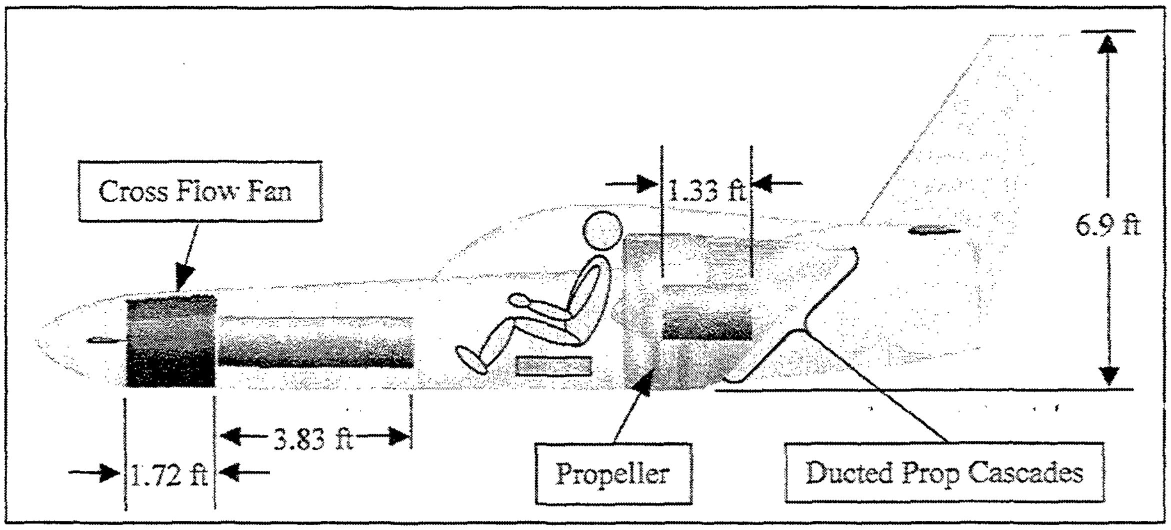

Figure 9. Side Semi-transparent View of VTOL Aircraft Design.

VIII. PERFORMANCE

The initial weight goal of 1,000 lbf proved to be too optimistic. The cross flow fan unit could not be designed with a large enough thrust-to-weight ratio with the chosen engines. In addition, at gross weights less than approximately 1,300 lbf, the weight balance required the pilot to be located coincident with the ducted fan units. The problems posed by this pilot station were either poor visibility with low mounted ducted propeller units or additional weight required to mount either the ducted propeller units or the pilot above the other. The best solution for the chosen equipment was to accept a gross weight increase to 1,330 lbf. The configuration chosen is a single cross flow fan unit and two ducted propeller units, which locates the vertical thrust centers in a triangular configuration.

Airfoil coordinate data for the NASA/Langley LS(1)-0413 was obtained from the University of Illinois at Urbana-Champaign web site [Ref. 8]. A panel code evaluation program named UPOT, developed at the Naval Postgraduate School, was used to evaluate the airfoil. Since the wing design is of high aspect ratio, the wing has a small chord length and consequently a small Reynolds number (Re) for the intended flight regime. For the initial airfoil analysis, a Re of 2.0×10^6 was used since that is lowest Re that provides consistent results in UPOT. Reynolds numbers for the final design actually vary from approximately 1.14×10^6 for the wing at maximum range to 5.95×10^5 for the canard at maximum endurance. The C_{D0} for the airfoil (0.010), which was calculated in UPOT with the Squire-Young empirical drag formula, was approximated by matching the angle of attack at zero lift to the same angle of attack on a C_D versus angle-of-attack plot created by UPOT. Observation of the boundary layer separation calculations in UPOT led to estimation of the two-dimensional airfoil maximum lift coefficient (C_{Lmax}) at 1.17. The drawback to this airfoil shape is the high stall speed that would require a longer vertical thrust duration and a larger fuel weight fraction for this flight regime. Further analysis could identify an airfoil shape that optimizes the tradeoff between low drag and low stall speed. The drag polar for the LS(1)-0413 airfoil, as derived from UPOT, is shown in Figure 10. Unfortunately, the relatively small number of airfoil data points available for this profile causes the spline-fit UPOT airfoil surface to be uneven (not smooth) and consequently the calculated drag values to vary considerably.

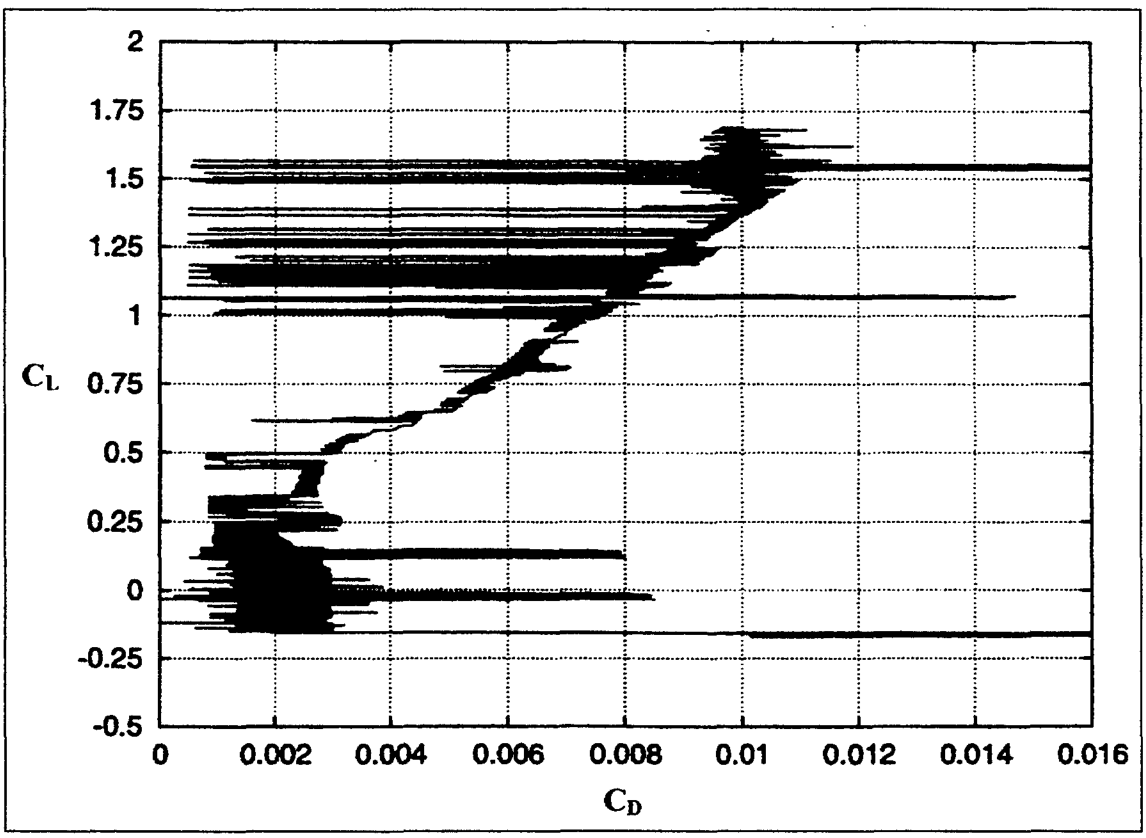

Figure 10. Drag Polar (CL vs. CD) for LS(1)-0413 2-D Airfoil (from UPOT).

After correcting the two-dimensional lift-curve slope to a three-dimensional wing, with an aspect ratio of 20 and an assumed 0.85 Oswald's efficiency factor, standard maximum range and endurance relationships for C_{D0} and C_{Di} were used to determine the three-dimensional wing lift and drag coefficients. A basic airframe was drawn in Rapid Aircraft Modeller (RAM), a NASA program, with a SC(2)-0413 airfoil profile for the wing and canard. Aerodynamic properties of the RAM model were then estimated using VORVIEW, a NASA vortex panel code program. The drag estimate from VORVIEW was then used to calculate the thrust and power required for forward flight at maximum range and endurance airspeeds. Estimated performance of the aircraft in forward flight is summarized in Table 1., based on an altitude of 10,000 feet above mean sea level and a gross weight of 1,330 lbf.

Table 1. Forward Flight Performance Values.

@ 10,000 feet MSL	Maximum Range	Maximum Endurance
Airfoil		
C_L	0.73	1.26
C_D	0.02	0.04
(C_L/C_D)max	36.5	-
$(C_L^{3/2}/C_D)$max	-	31.6
Angle of Attack	0.31°	3.8°
Re (wing/canard)	1.14×10^6 / 7.84×10^5	8.69×10^5 / 5.95×10^5
True Airspeed	258 ft/sec (153 KTAS)	196 ft/sec (116 KTAS)
Stall Airspeed	148 ft/sec (88 KTAS)	148 ft/sec (88 KTAS)
Aircraft		
CL	0.8696	1.5067
CD	0.0456	0.0799
L/D	19.1	18.9
Thrust Required	69.7 lbf	70.4 lbf
Power Required	33 hp	25 hp

The minimum fuel quantity required was estimated using the specific fuel consumption in Reference 3 of 0.4 lbf per hp-hr. For a round trip, total vertical flight time was assumed to be 15 minutes (or 0.25 hours), 3.4 hours of forward flight time and 0.3 hours of reserve fuel flight time. To arrive at the weight of fuel burned, the specific fuel consumption is multiplied by the total horsepower required which is then multiplied by the flight time.

Table 2. Thrust and Weight Figures.

Configuration	A	B	C	D
Total Weight Goal (lbf)	1,200	1,200	1,200	1,332
1.3 x Total Wt. (lbf)	1,560	1,560	1,560	1,732
Cross Flow Fan				
Motor	4 rotor	6 rotor	8 rotor	8 rotor
RPM	6,500	6,500	6,500	6,500
hp	300	450	600	600
Thrust (lbf)	345	518	690	690
Thrust/Weight	1.9	2.0	2.2	2.2
Fan Span (feet)	0.858	1.292	1.717	1.717
Engine Length (feet)	1.75	3	3.83	3.83
Weight (lbf)	182	254	308	308
Ducted Fans				
Motor	2 x 3 rotor	2 x 2 rotor	2 x 2 rotor	2 x 2 rotor
RPM	4,500	6,500	6,500	6,500
hp	300	300	300	300
Thrust (lbf)	1,215	1,042	870	1,042
Thrust/Weight	3.7	3.7	3.1	3.7
Engine Length (feet)	1.75	1.33	1.33	1.33
Prop Diameter (feet)	3.41	2.78	2.24	2.78
Prop Tip Speed (ft/sec)	813	947	762	947
Weight (lbf)	330	280	280	280
Fuselage Weight (lbf)	195	195	195	195
Wing Weight (lbf)	77	77	77	77
Canard Weight (lbf)	58	58	58	58
Passenger Weight (lbf)	250	250	250	250
Fuel Weight (lbf)	128	134	140	140
Total Weight (lbf)	1,240	1,268	1,328	1328
Total Thrust (lbf)	1,560	1,560	1,560	1,732
Total Thrust/Weight (lbf)	1.258	1.230	1.175	1.304

Table 2 shows results for four different power plant combinations, based on weight estimations as described previously. Configuration D provides the desired thrust-to-weight ratio, and allows the pilot to be positioned forward of the ducted propeller nacelles. This weight analysis is only an approximation, using the information available, to determine if further study is appropriate for an aircraft of the configuration specified. A more detailed analysis would include landing gear, computer(s), and all of the sundry items required to construct an actual aircraft.

Due to the desire for a direct connection of the propellers to the engines, the maximum thrust produced by the ducted propeller units is limited by tip speed. The maximum combined thrust for two ducted fan units is approximately 1,042 lbf when driven at 6,500 rpm with 150 horsepower. Use of 150 horsepower, 2 rotor, 4,500 rpm engines would provide a maximum thrust of about 1,330 lbf but the propeller diameter would be slightly greater than 3.8 feet, and the width of two ducted fan units alone would be nearly 8 feet – increasing overall width to one which would not fit in an automobile parking space. It appears that the limiting factor in this design study is the thrust per weight ratio of the cross flow fan and engine unit. Substantial power increases from turbo- or super-charging, with minimal weight increases, would improve the thrust-to-weight ratio. Higher horsepower engines would either allow more thrust and longer fan blade span for a given engine size or a smaller engine for the same current power rating. This could allow the potentially more ideal configuration of two cross flow fan units for vertical thrust augmentation and one ducted propeller unit for lift/cruise propulsion.

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IX. STABILITY

The centers of the vertical thrust are in a triangular configuration. Forty percent of the maximum thrust is produced by the forward located cross flow fan, and the remaining sixty percent comes from the two aft ducted propellers. Component locations were chosen to have a near zero longitudinal moment at maximum vertical thrust as shown in Figure 10. In addition to control of thrust output by throttle, both the louvers on

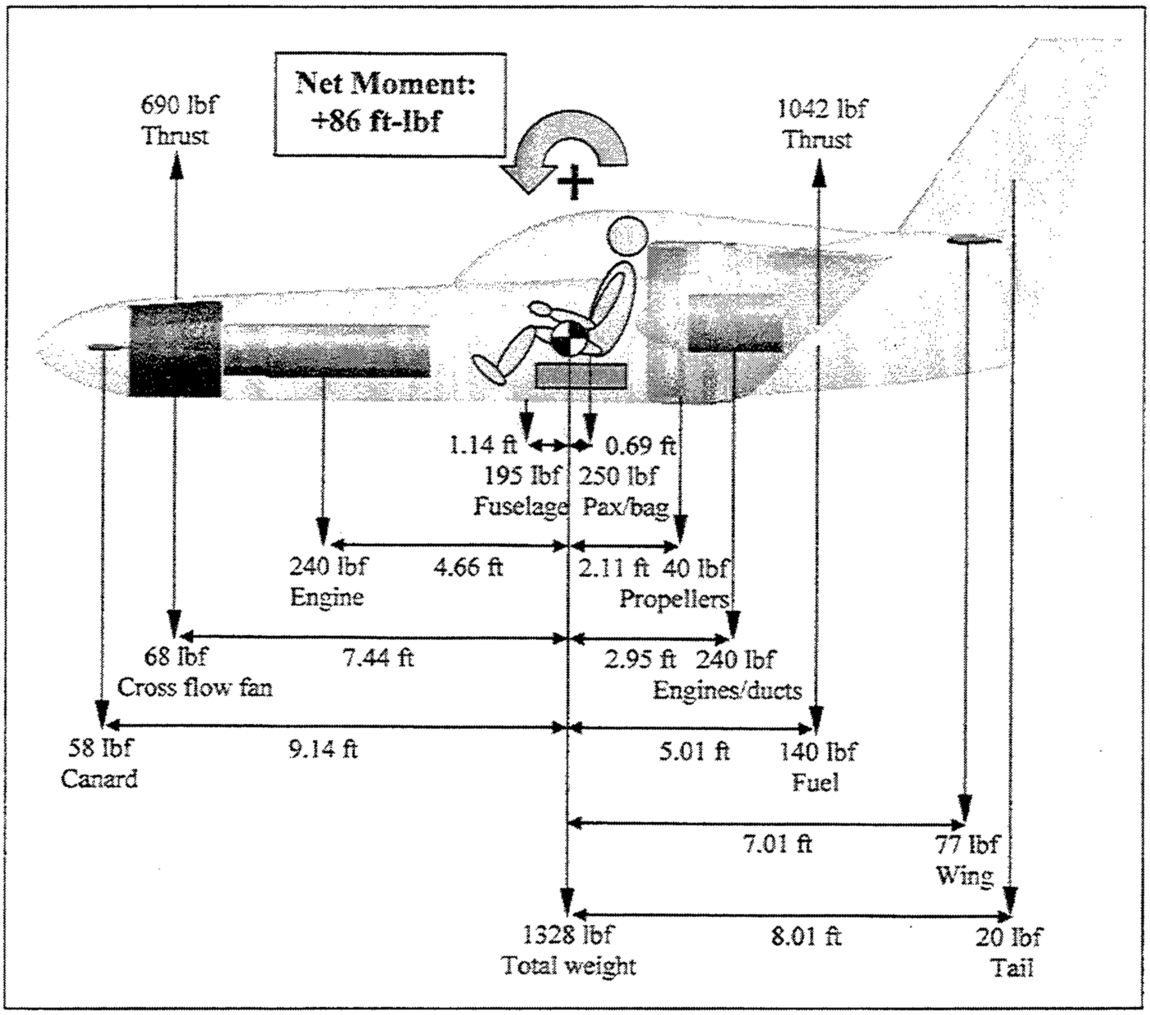

Figure 11. Weight and Balance of VTOL Aircraft Design.

the cross flow fan and the cascade exit vanes on the ducted propellers can be actuated to provide thrust vectoring in vertical flight for control of fore and aft motion, pitch, roll and yaw. The ducted propellers are displaced a relatively small distance from the longitudinal axis, but the rolling moment of inertia should be small enough to allow more than adequate lateral control with thrust due to the light weight of the wing and canard.

X. CONCLUSIONS AND RECOMMENDATIONS

The cross flow fan is a viable solution, but further study is required to fully understand the design and its limitations. The data used for this report indicates that improvements in design could increase the thrust output to power input of the cross flow fan, but probably not drastically. The methodology which LTV used in designing the cross flow fan in their study was not presented, and design variations were not extensively tested. The optimum design parameters for cross flow fans have yet to be defined.

The largest drawback of the cross flow fan for lightweight applications is the large amount of power required to produce adequate thrust. The engines used for this study were not turbocharged. Most, if not all, current aircraft turbocharging applications are designed to provide somewhat constant thrust from takeoff to medium altitudes, but lightweight commuter VTOL aircraft as proposed in this report would not have the same power requirements. Maximum thrust is needed only for takeoff and landing, and the vertical thrust augmentation is used only at low altitude. Power output of the rotary engines could be greatly increased by turbocharging for maximum power at low altitudes. Another option is to use higher performance engines -- the 1991 Le Mans winning Mazda 787B used a four-rotor rotary engine which produced 700 hp at 9,000 rpm [Ref. 9].

The aircraft designed in this study demonstrates the potential for use of cross flow fan propulsion. Further study is required, and warranted, to determine the ultimate feasibility of this type of propulsion.

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1. Naval Air Systems Command Contract N00019-74-C-0434, *Multi-Bypass Ratio Propulsion System Technology Development*, Vol. I pp. 3-6, 3-9, 3-41, Vol. II pp. 2-18, Vol. III pp. 2-6, 2-7, Vought Systems Division, LTV Aerospace Corporation, 24 July 1975.

2. Mazur, Joseph S., *A Study of The Cross Flow Fan*, pp. 80, 96-100, Ph.D. Dissertation, Wayne State University, Detroit, Michigan, 1984.

3. Freedom Motors, "Specifications for 530 Series Engines", [http://www.freedom-motors.com], 2000.

4. Kohlman, David L., *Introduction to V/STOL Airplanes*, pp. 19-26, Iowa State University Press, Ames, Iowa, 1981.

5. Prouty, Raymond W., *Helicopter Performance, Stability, and Control*, pp. 1-9, Krieger Publishing Company, Malabar, Florida, 1995.

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7. Cook, Woodrow L., *Summary of Lift and Lift/Cruise Fan Powered Lift Concept Technology*, pp. 2-8, NASA Contractor Report 177619, August 1993.

8. University of Illinois at Urbana-Champaign, "Airfoil Database", [http://www.uiuc.edu/ph/www/m-selig/ads/coord_database.html], 2000.

9. Marr, Alan, "Rotary Combustion Engine Data", [http://www.monito.com/wankel/engines.html], 2000.

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APPENDIX. PRESENTATION SLIDES

The appendix contains reproductions of the Microsoft Powerpoint slides used for the thesis presentation.

Investigation of Cross Flow Fan Propulsion for Lightweight VTOL Aircraft

LCDR Dean Gossett

Naval Postgraduate School

Advisor: Prof. Max Platzer

Co-Advisor: Dr. Kevin Jones

Overview

- Mission Statement
- Design Considerations
- Rotary Engine
- Cross Flow Fan
- Aircraft Design
- Performance
- Stability
- Summary

Mission Statement

- Lengthy commutes by automobile in congested areas
- Number of airports and locations inconvenient
- Commuter VTOL aircraft
  - From driveway to work, and back
  - Small size, short range, 1000 lbf weight
  - Lift/cruise propulsion with VTOL thrust augmentation
  - Aerodynamics optimized for forward flight
- No special launch or recovery requirements
- Minimal danger to pedestrians

Design Considerations

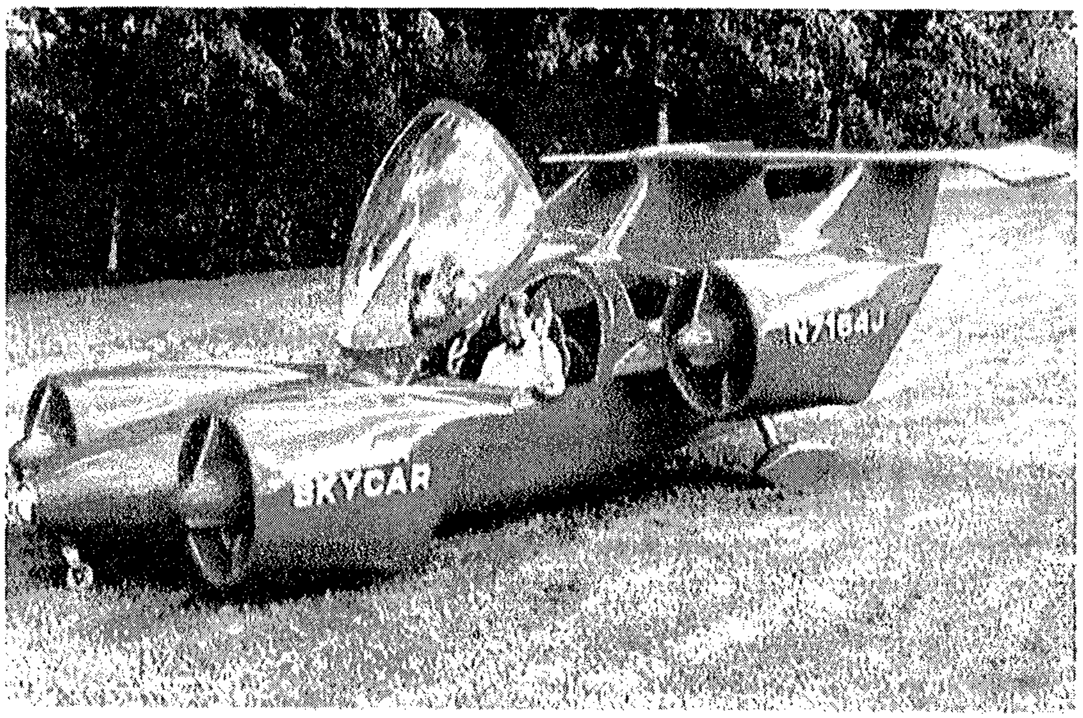
- Airframe
  - Bare minimum equipment
  - Single seat
  - Composite materials
  - Expect weight similar to sailplane
  - Wing/canard or conventional configuration
  - 350 lbf goal
  - 250 lbf maximum for pilot and bags
- Thrust – 1.3 times gross takeoff weight

Design Considerations

- Ducted propellers for lift/cruise
  - At least 1.26 times static thrust of similar unducted propeller
  - Good thrust/weight
  - Pedestrian safety
- Cross flow fan
  - Small cross section
  - Within fuselage
- Rotary engine
  - Small, good power/weight (2.5)
- Turbine engine
  - Good power/weight (2.86)
  - Heat, noise

Design Considerations

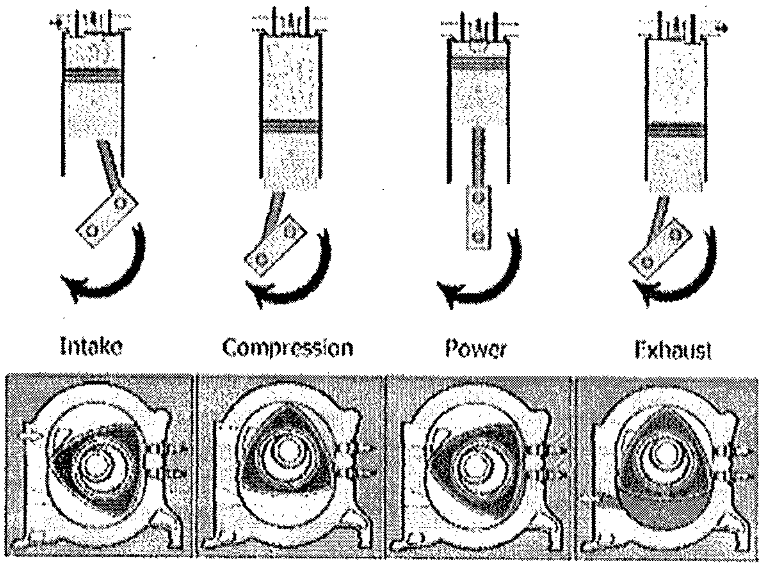
- Moller International Volanter VTOL aircraft
  - Ducted propellers for lift/cruise
  - Relies on vectored thrust for lift in forward flight - inefficient

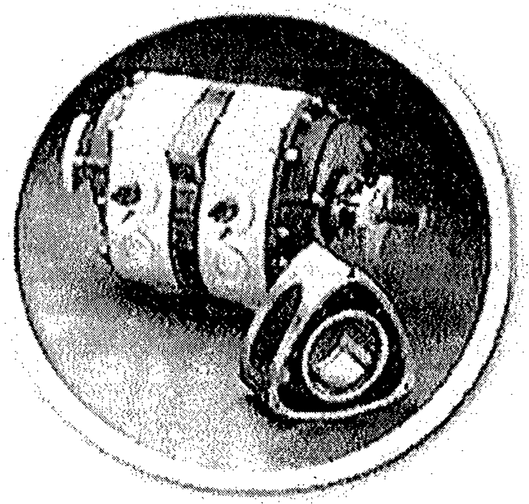


Rotary Engine

- Rotapower® 530 series from Freedom Motors
- Modular design
- 11 inches high, 11 inches wide
- SFC = 0.4 lbf/hp-hr (w/ proprietary cylinder coating)
- 2 specifications
  - Industrial - 4500 rpm
  - High performance - 6500 rpm (50% more power)
- Horsepower per pound weight ratio
  - 1.67 - 2 rotor high performance
  - 2.50 - 8 rotor high performance

Rotary Engine

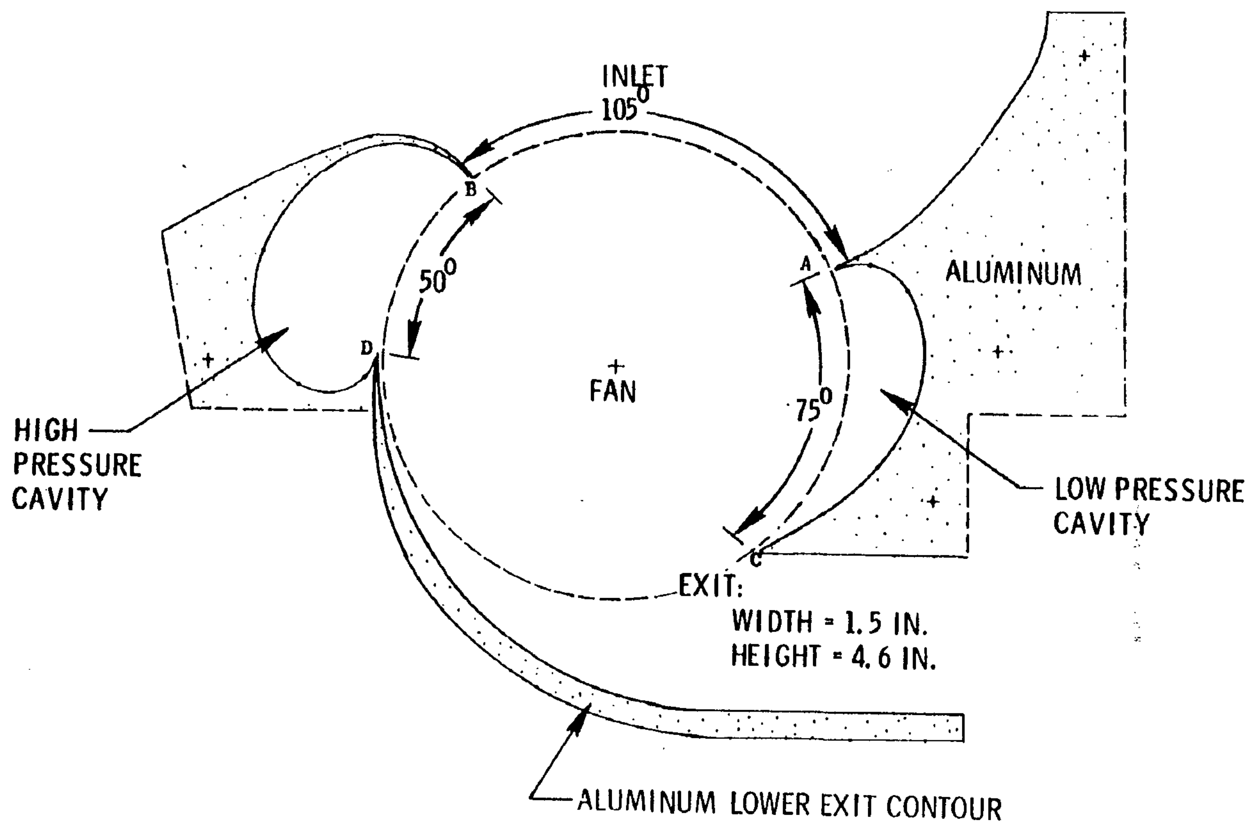




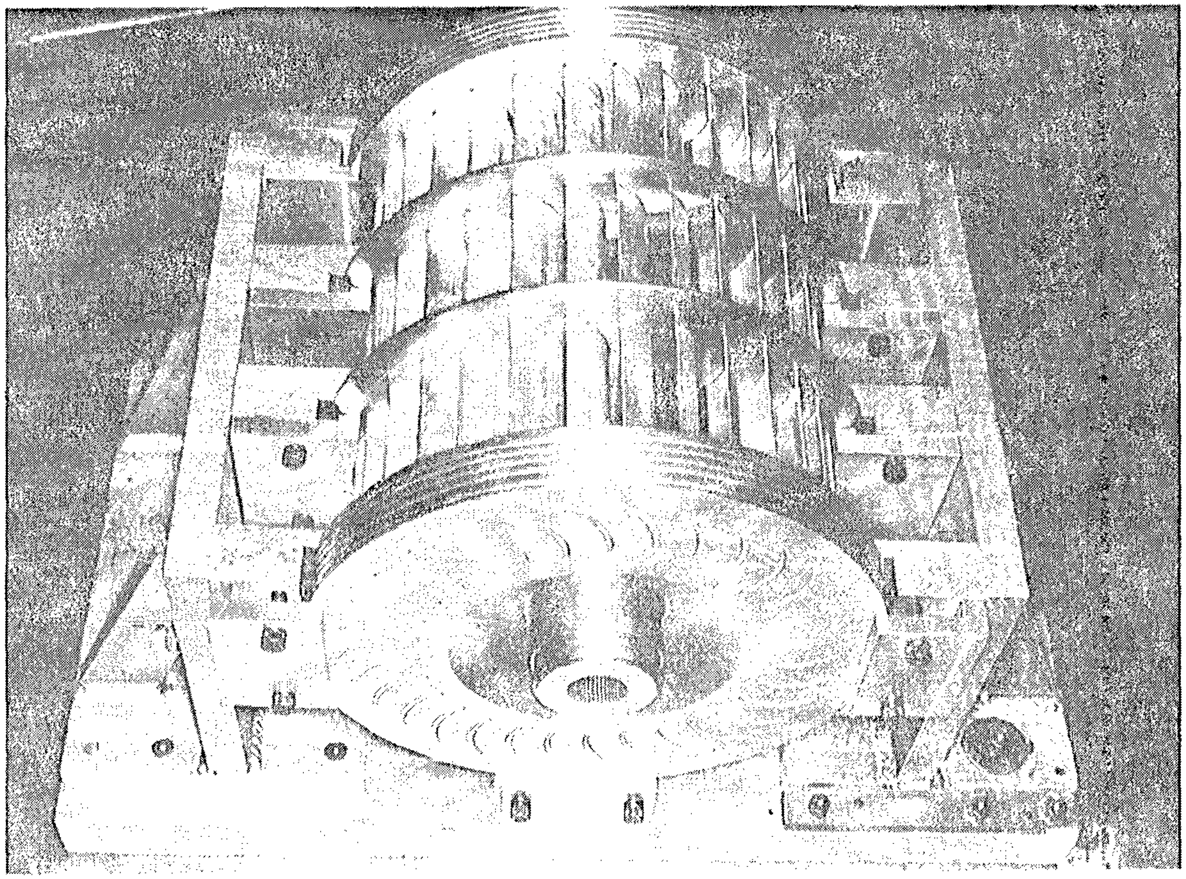
Cross Flow Fan

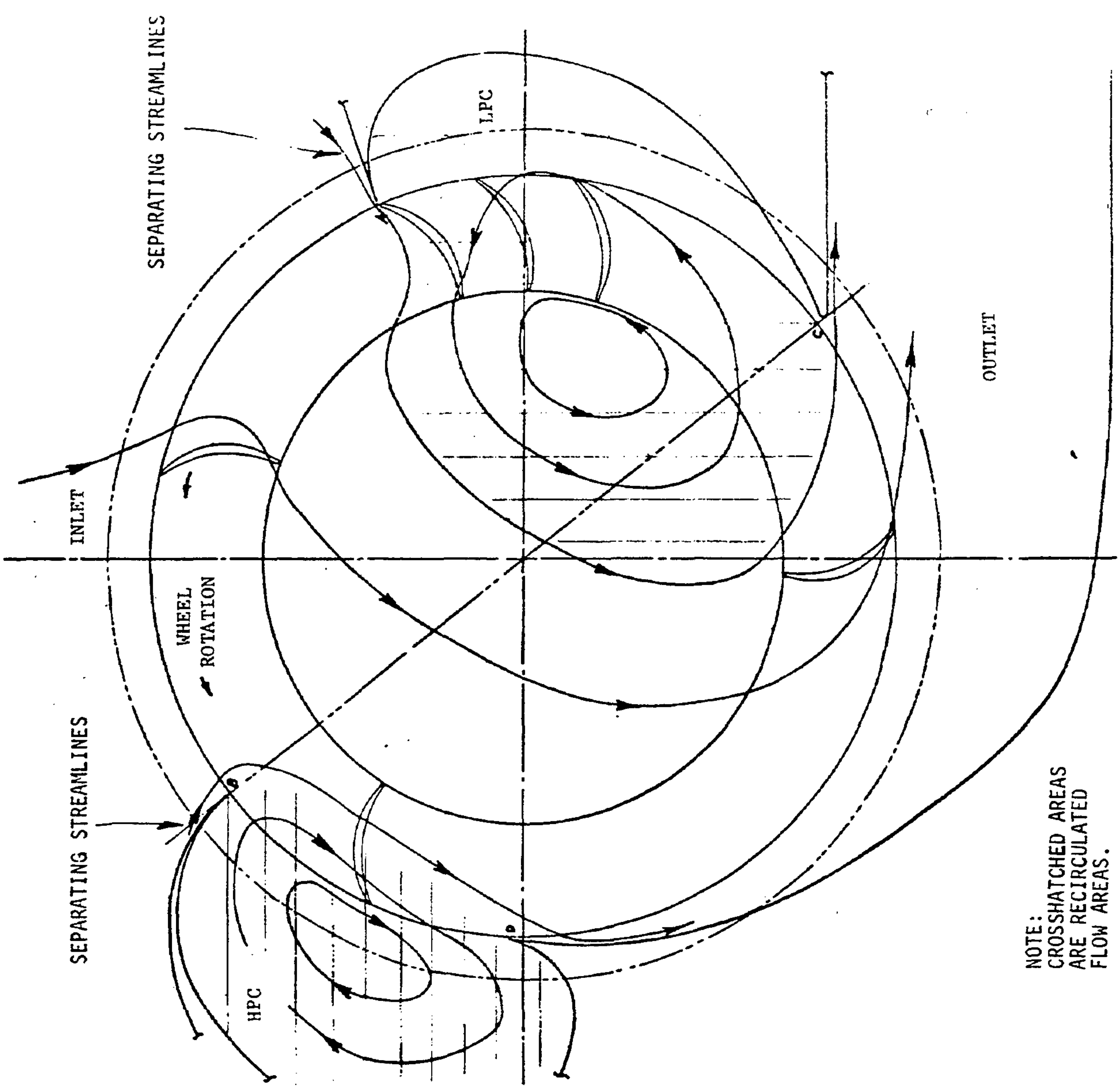
- Current uses
  - Entry ways
  - Electronics cooling
- Optimal design not defined
- Most recent testing
  - LTV in 1974 for VTOL aircraft (Navy contract)
  - Dr. Joseph Mazur in 1985 for dissertation

Cross Flow Fan



Cross Flow Fan



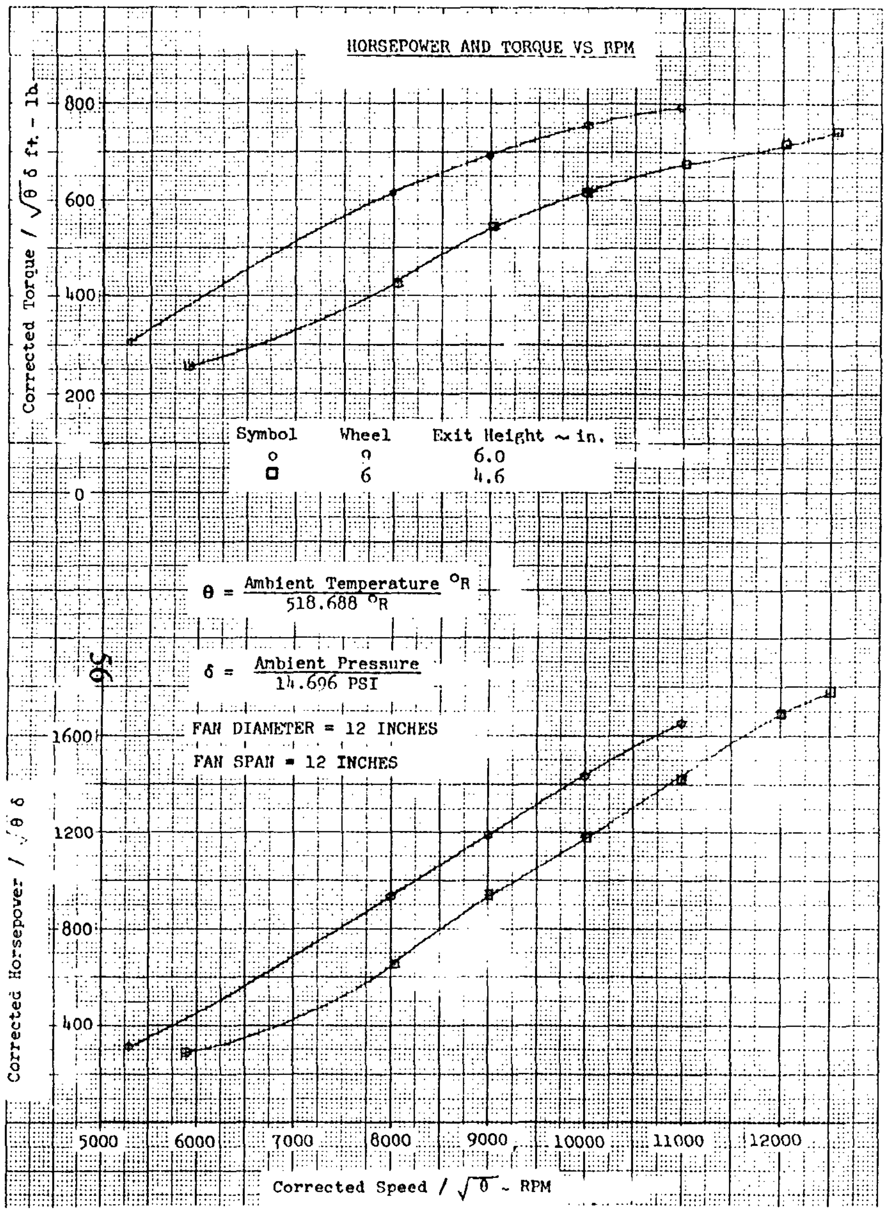

SEPARATING STREAMLINES
LPC
SEPARATING STREAMLINES
INLET
WHEEL ROTATION
OUTLET
HPC
NOTE:
CROSSHATCHED AREAS
ARE RECIRCULATED
FLOW AREAS.

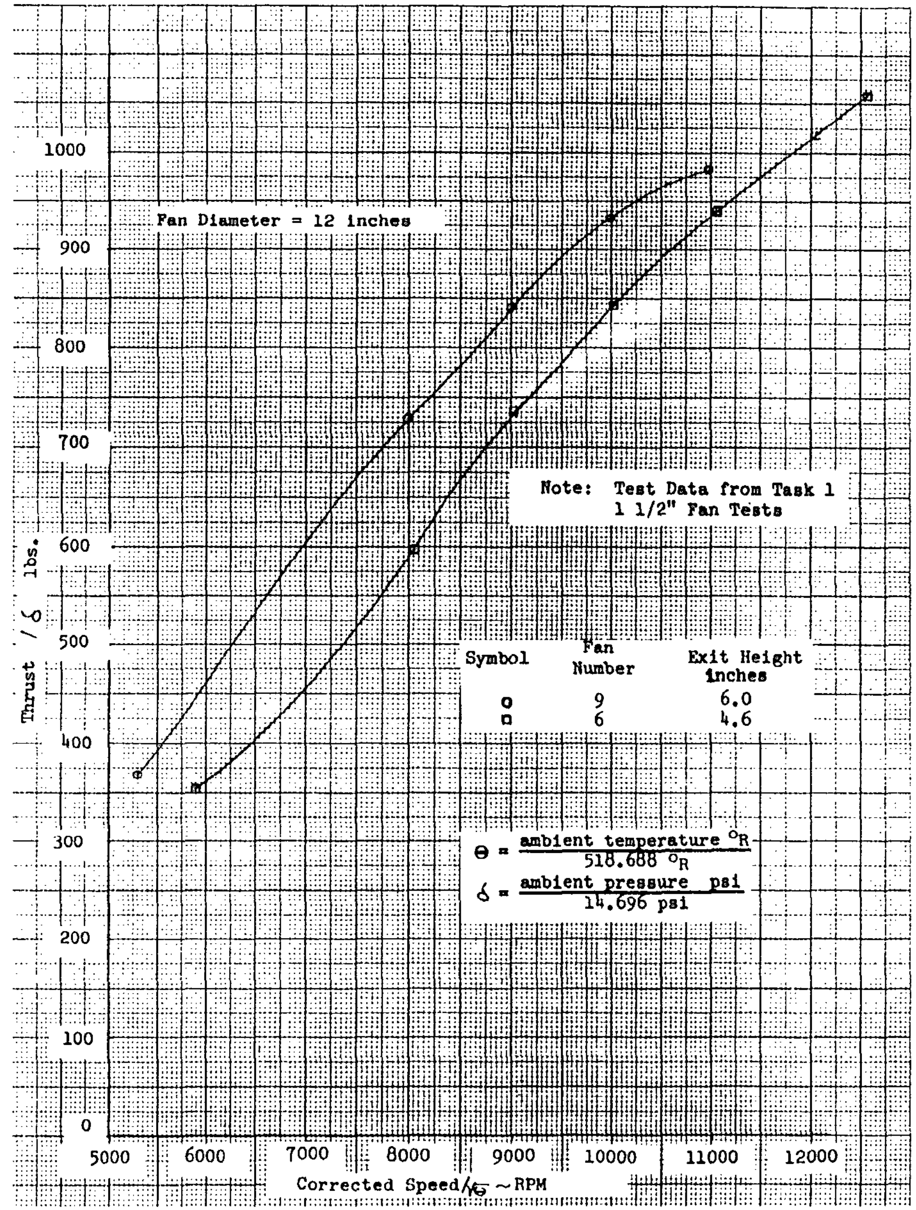
Cross Flow Fan

- Air flow is perpendicular to rotation axis
  - Mostly 2-D
  - Output proportional to blade span
- Fan performance effected by
  - Fan rotation speed
  - High and low pressure cavity shape
  - Clearance between fan blades and cavities
  - Fan blade chord
  - Exit duct height

Cross Flow Fan

- LTV tested 12 inch diameter fan
- Data in report
  - 1.5 inch and 12 inch blade spans
  - 2 blade shapes
  - 2 exit duct heights
- Compression efficiency 70% to 80% at 4000 to 7000 rpm
- Thrust (lbf) output per horsepower input
  - Fan #6, 4.6 inch exit height: 1.15 at 6500 rpm
  - Fan #9, 6.0 inch exit height: 0.95 at 6500 rpm


HORSEPOWER AND TORQUE VS RPM
Corrected Torque / $\sqrt{\theta}$ δ ft. - lb.
800
600
400
200
0
Symbol Wheel Exit Height ~ in.
○ 9 6.0
□ 6 4.6
$\theta = \frac{\text{Ambient Temperature } ^\circ R}{518.688\ ^\circ R}$
$\delta = \frac{\text{Ambient Pressure}}{14.696 \text{ PSI}}$
FAN DIAMETER = 12 INCHES
FAN SPAN = 12 INCHES
Corrected Horsepower / $\sqrt{\theta}$ δ
1600
1200
800
400
5000
6000
7000
8000
9000
10000
11000
12000
Corrected Speed / $\sqrt{\theta}$ ~ RPM


Fan Diameter = 12 inches
Thrust / δ lbs.
1000
900
800
700
600
500
400
300
200
100
0
Note: Test Data from Task 1
1 1/2" Fan Tests
Symbol Fan Number Exit Height inches
○ 9 6.0
□ 6 4.6
$\theta = \frac{\text{ambient temperature } ^\circ R}{518.688\ ^\circ R}$
$\delta = \frac{\text{ambient pressure psi}}{14.696 \text{ psi}}$
5000
6000
7000
8000
9000
10000
11000
12000
Corrected Speed/$\sqrt{\theta}$ ~ RPM

Cross Flow Fan

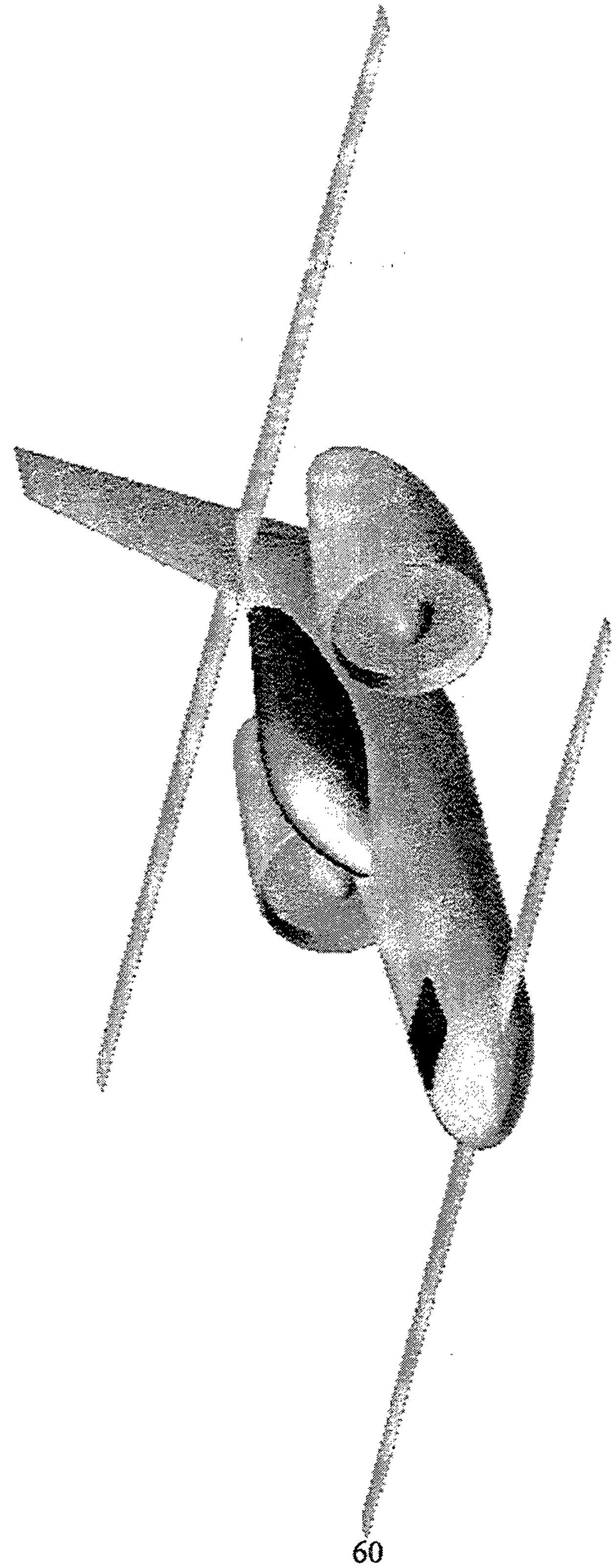
- VTOL Cross Flow Fan design
  - 600 hp, 6500 rpm, 8 rotor engine
  - 20.6 inch (1.717 feet) fan span
  - 308 lbf weight
    - Engine: 240 lbf
    - Fan: 25 lbf (pultruded and bonded carbon/epoxy)
    - Ducts and cavities: 33 lbf (aluminum sheet and honeycomb)
  - 690 lbf thrust
  - 2.2 thrust/weight ratio
- Weights are scaled from LTV and Freedom Motors data

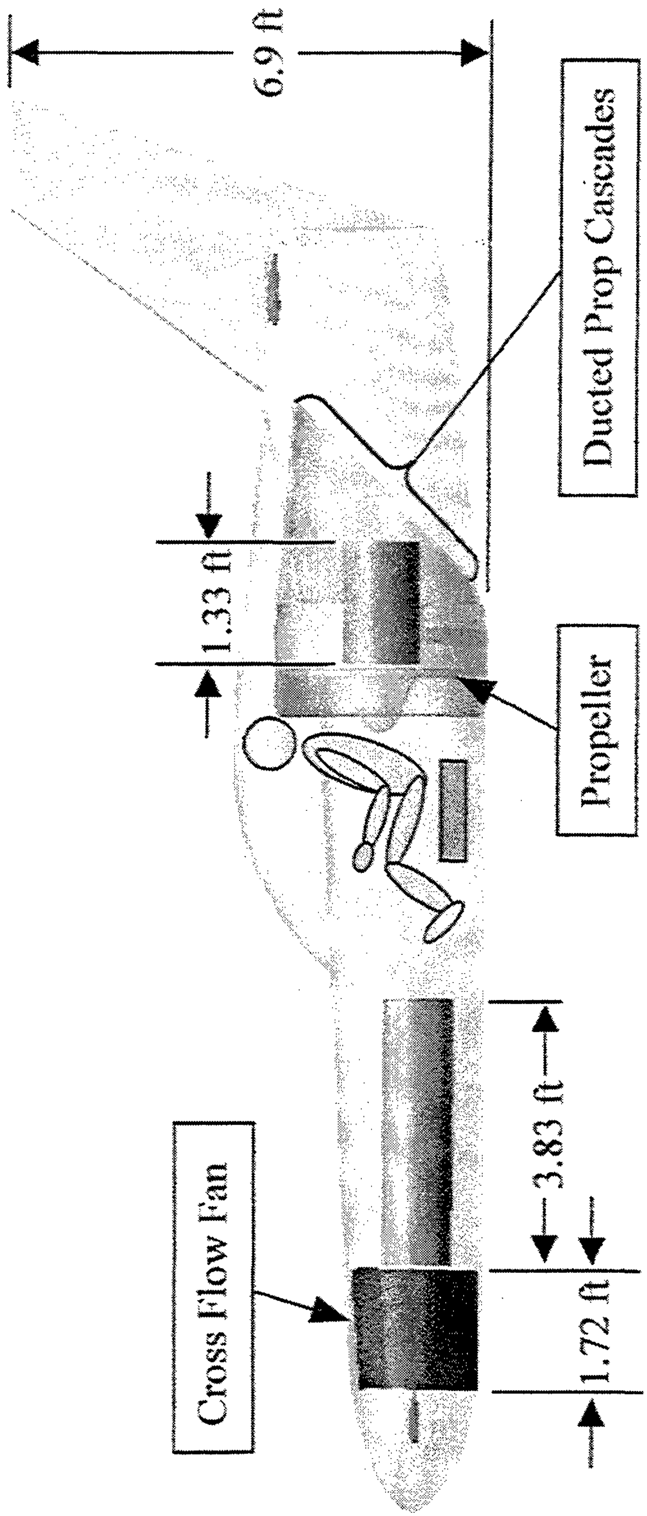
Aircraft Design

- Wing/canard configuration
  - Weight and balance
  - Both contribute to lift
- NASA/Langley LS(1)-0413 airfoil
  - Low drag at zero lift and at C_L 0.5
  - Aspect ratio - 20
- VTOL thrust augmentation
  - Cross flow fan within forward fuselage
  - Inlet/exhaust louvers
    - Flush when thrust augmentation not required
    - Vector for yaw control and transition to forward flight

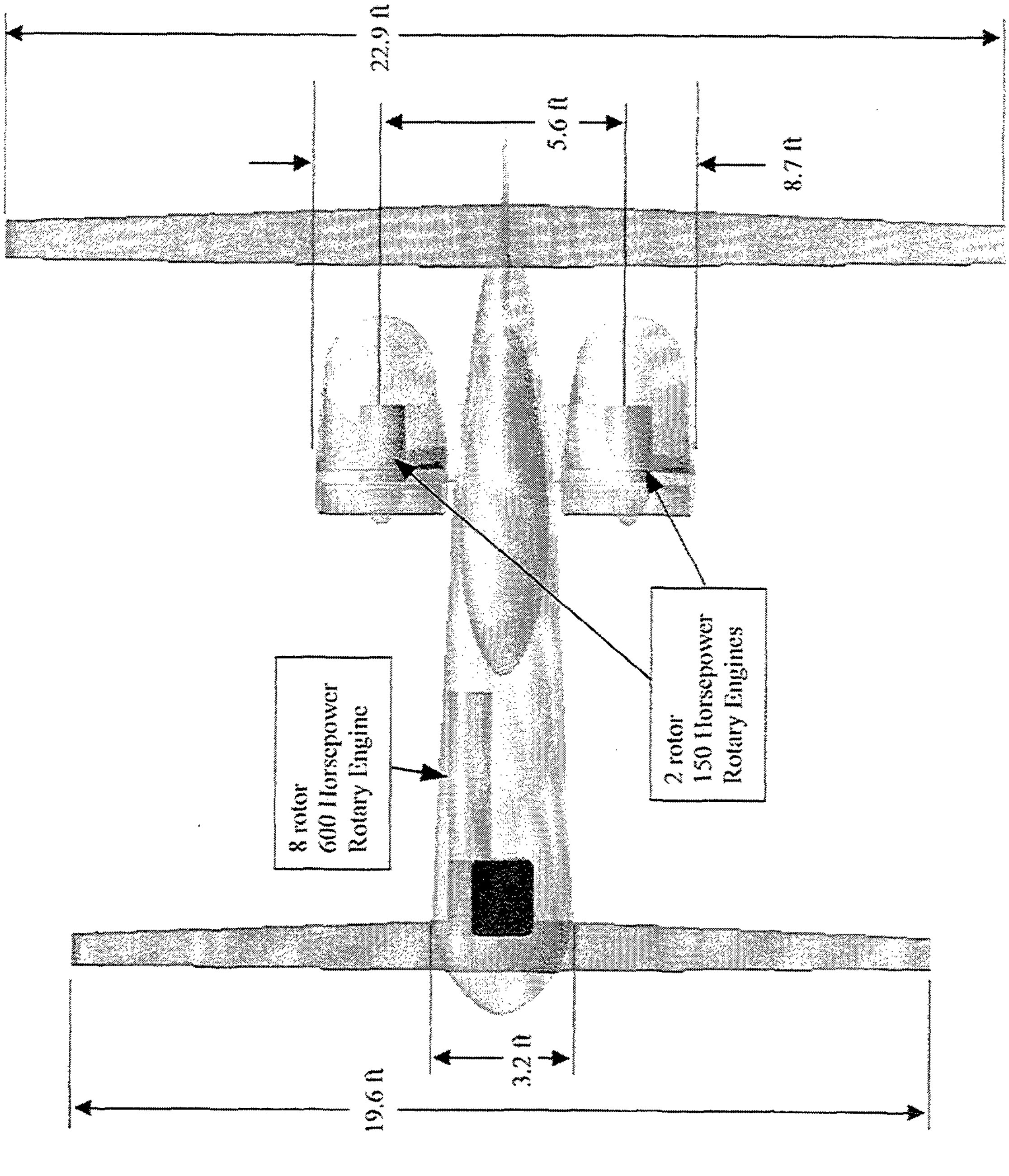
Aircraft Design

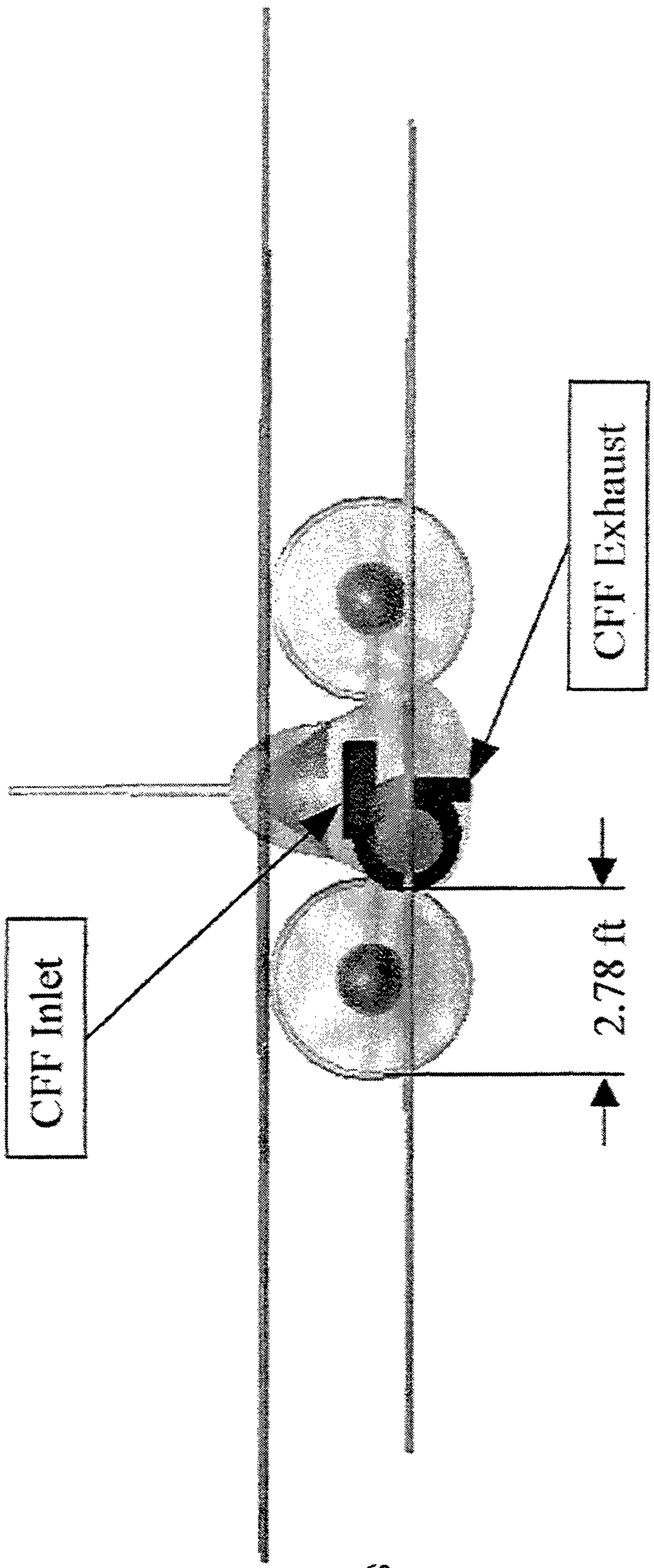
- Lift/cruise thrust
  - 2 ducted propellers mounted aft of CG
  - Small propeller
  - Direct drive from 6500 rpm engine
  - Cascade exit vanes vector thrust
- Removable or foldable wing/canard sections
- Good pilot visibility
- 1,330 lbf gross weight





6.9 ft
Ducted Prop Cascades
1.33 ft
Propeller
3.83 ft
1.72 ft
Cross Flow Fan


22.9 ft
5.6 ft
8.7 ft
2 rotor
150 Horsepower
Rotary Engines
8 rotor
600 Horsepower
Rotary Engine
3.2 ft
19.6 ft


CFF Inlet
CFF Exhaust
2.78 ft

Aerodynamic Performance

@ 10,000 ft MSL	Max Range	Max Endurance
Vinf	258 ft/sec (153 KTAS)	196 ft/sec (116 KTAS)
Vstall	148 ft/sec (88 KTAS)	148 ft/sec (88 KTAS)
Thrust required	90 lbf	70 lbf
Power required	42 hp	25 hp

(from UPOT, RAM, and Vorview)

Cross Flow Fan Performance

Engine	4 rotor	6 rotor	8 rotor
RPM	6,500	6,500	6,500
Hp	300	450	600
Fan span (ft)	0.858	1.292	1.717
Thrust (lbf)	345	518	690
Weight (lbf)	182	254	308
Thrust/Weight	**1.9**	**2.0**	**2.2**

Ducted Propeller Performance

Engines	2 x 3 rotor	2 x 2 rotor
RPM	4,500	6,500
Hp	300	300
Prop diameter (ft)	3.41	2.78
Tip speed (ft/sec)	813	947
Thrust (lbf)	1,215	1,042
Weight (lbf)	330	280
Thrust/Weight	3.7	3.7

Final Design Performance

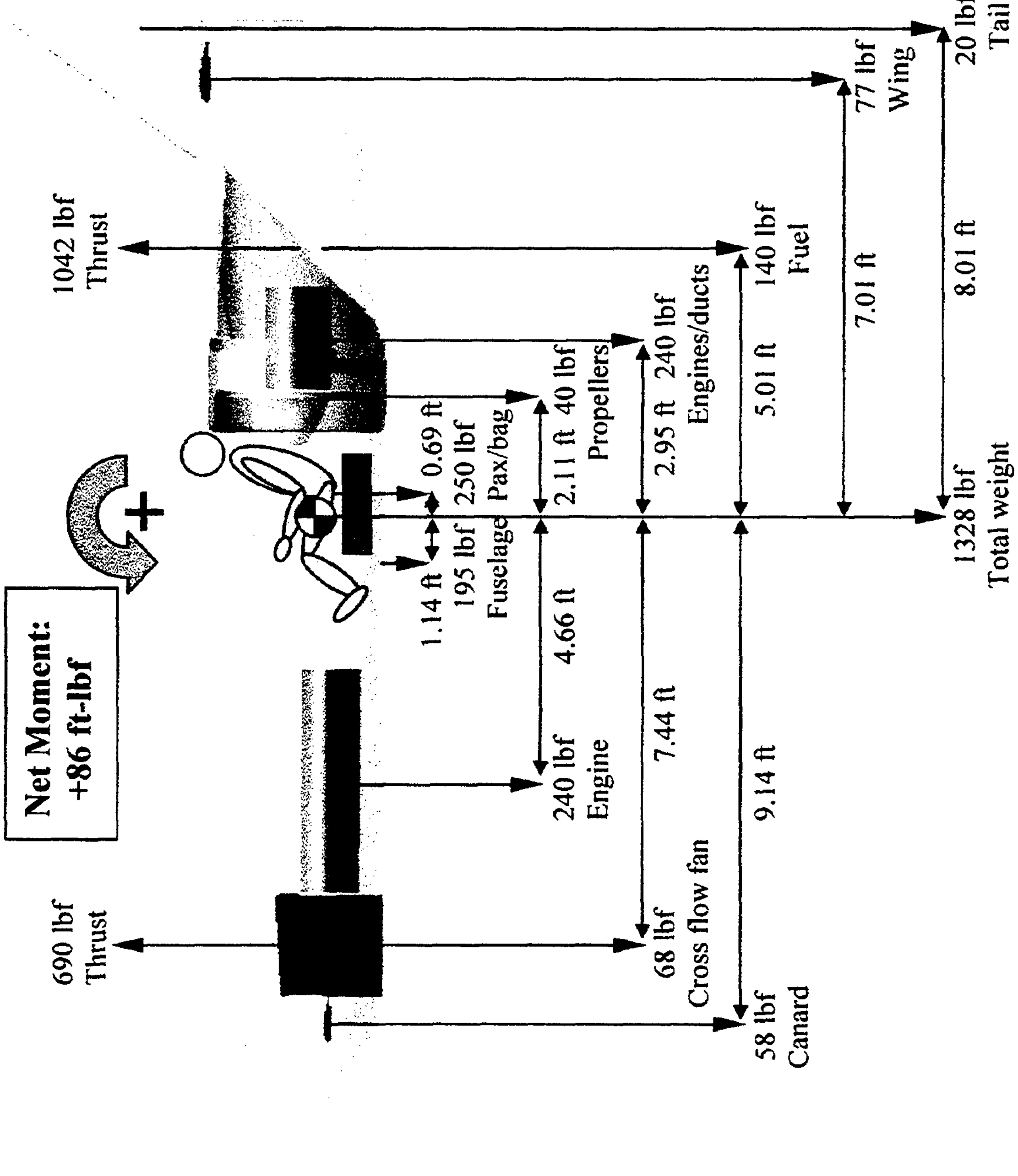
Thrust (lbf)	
Cross flow fan	690
Ducted fans	1,042
Total	1,732
Weight (lbf)	
Fuselage/wing/canard	350
Passenger/baggage	250
Cross flow fan/engine	308
Ducted propellers/engines	280
Fuel	140
Total	1,328
Total Thrust/Weight	**1.304**

Fuel Consumption

- Assumptions
  - 12 minutes total VTOL for round trip
  - 3.8 hours forward flight time round trip (580 nm total)
  - 0.3 hours reserve fuel
- SFC = 0.4 lbf/hp-hr
- Fuel consumed
  - SFC x hp_{req} x flight time
    - (0.4)(900 hp)(0.2 hr) = 72 lbf
    - (0.4)(57 hp)(3.8 hr) = 60 lbf
    - (0.4)(57 hp)(0.3 hr) = 8 lbf
    - **Total fuel required = 140 lbf**

Stability

- Differential thrust
  - Vectored thrust
  - Electronic throttle (total thrust) control
- Lateral
  - Ducted propellers
- Longitudinal
  - Cross flow fan/Ducted propellers
- Yaw
  - Cross flow fan louvers (ducted propellers)
- Gyro-assisted computer control



Net Moment:
+86 ft-lbf
690 lbf
Thrust
1042 lbf
Thrust
58 lbf
Canard
68 lbf
Cross flow fan
240 lbf
Engine
1.14 ft
195 lbf
Fuselage
0.69 ft
250 lbf
Pax/bag
2.11 ft
40 lbf
Propellers
2.95 ft
240 lbf
Engines/ducts
5.01 ft
140 lbf
Fuel
7.01 ft
77 lbf
Wing
8.01 ft
20 lbf
Tail
4.66 ft
7.44 ft
9.14 ft
1328 lbf
Total weight

Summary

- Cross flow fan is viable, but
  - Large horsepower requirement
  - Horsepower = weight
    - Turbocharging could increase power/weight ratio
  - Optimal design of blades and cavities unknown
  - Data available only for 12 inch diameter fan
- Extensive study required

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   Monterey, CA 93940